NEAR BED SOLIDS TRANSPORT IN COMBINED SEWERS

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I certify that this is the true and accurate version of the thesis approved by the examiners.

Signed........[redacted]...... Date..8/10/96
(Director of S[redacted]

Abstract

Concern regarding the problems associated with sediments in sewers, and their transport through these systems, has given rise to concerted research programmes in the U.K., and further afield. A collaborative research project was initiated in collaboration with the University of Newcastle upon Tyne, the University of Sheffield and Tayside Regional Council Department of Water Services, under the auspices of the UK Sewer Sediments Research Group, which originally reported to the Urban Pollution Management (UPM) Programme Steering Group. The work of the Wastewater Technology Centre, at University of Abertay Dundee, has been fundamental in collecting data for the UPM programme over the last 10 years, and the work presented in this thesis represents a key aspect of this work.

Current knowledge regarding the movement of sediments in sewerage systems is reviewed. Additionally, the attempts to model sediment transport in laboratory flumes is examined, and the application of these models is discussed. Differences between the material used in laboratory studies and that experienced in existing field studies is highlighted. Different modes of sediment transport in sewers are theorised, and differences in the material moving in the respective modes of transport in various studies are examined

The study reported here examines the nature of the material in transport in sewers in general, however the solids moving at the bed are dealt with in particular. A methodology is established which is suitable for the collection of material moving near the bed in sewers in Dundee. Based on data collected from three separate, non-concurrent field sites, observations are made regarding the nature of the material in transport near the bed. Comparisons are made between the nature of the material in transport at the bed at each of the field sites, and the material is compared with the sewage sampled concurrently. Temporal and spatial variations in the material in transport at the bed at each of the study sites are highlighted. The mass of solids transport, and associated pollutant load, is compared with other modes of transport.

Using the data collected, contemporary sediment transport models are employed. A modified relationship is proposed for near bed sediment transport over a deposited bed. The difficulties in collecting the data required to apply laboratory based sediment transport models are highlighted.

A link is proposed between the pollutants observed in first foul flush phenomena and the pollutants associated with the material in transport at the bed in combined sewer systems in general.

Development of a novel methodology for estimating the rate of material transport at the bed of the Dundee system sites is described. The relationship obtained is demonstrated as representing four distinct factors: ambient hydraulic conditions; inputs to the system; transported material characteristics and upstream deposited bed characteristics.

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As the author of this thesis, I wish I could say that all the work reported herein is solely due to my hard work. However, in reality, I have relied heavily on a group of people for assistance, advice, and at times motivation to successfully complete this project. So it is only correct that, at the outset, I should acknowledge their assistance, although, I am sure, they are already aware that I am indebted to them.

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for marc

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Glossary of Terms

Apparent Yield Stress	Stress at which the rate of sediment sample deformation continually increases under constant applied stress during rheometrical testing
Ashed Residue	The remaining solid material in a sediment sample after placing in a furnace at 550°C for 30 minutes
Bed-Load	Material transported near to bed by saltation, rolling, sliding or a combination of all three
Biochemical Oxygen Demand (BOD)	Oxygen consumed by bacteria as a result of the concentration of organics in a sewage or sediment sample
Five Day Biochemical Oxygen Demand (BOD_5)	Oxygen consumed by bacteria as a result of the concentration of organics in a sewage or sediment sample over 5 days. The BOD_5 equals approximately 60-70% of the total BOD.
Chemical Oxygen Demand	A measure of organic material present in a sewage or sediment sample as a result of chemical oxidation
Cohesive Sediment	Sediment which exhibits cohesive properties (a tendency for the individual particles to adhere)
Combined Sewer	Sewer carrying both foul and storm sewage
Combined Sewer Overflow	A structure to relieve excess flow loading from a sewer
Critical Velocity	Flow velocity at which material begins to be entrained into the flow
Critical Yield Stress	Applied bed shear stress beyond which bed erosion commences
Deposition	The process by which suspended solids are deposited on the invert of a sewer to form a sediment deposit
Deposit Free Conditions	Hydraulic conditions which maintain solids in suspension without sediment deposition over a clear invert
Dry Weather Flow (DWF)	Sewer flow on days when there is no significant rainfall
Dry Weather Flow Pattern	The variation in DWF over a given duration
Dunes	Undulations on the surface of a deposited bed, or separate mounds of sediment on the invert.

Entrainment	Process of lifting near bed material into suspension
Erosion	Disturbance or lifting effect of flow causing the transfer of some or all of the material in a sediment bed into the near bed layer of transported material, or into suspension
First Foul Flush	Increased concentration of pollutants at the start of a storm event
Fluid Mud	Material transported close to the invert or sediment deposit, as a highly concentrated liquid.
Flume Traction	Bed-load transport without deposition
Foul Flow	Sewage in a combined (or separate) sewer originating from domestic and commercial premises which may include industrial effluent
Gross Solids	Large (>6mm) faecal and organic matter and other sewage debris
Impervious Surfaces	Surfaces which allow virtually no rainfall to percolate through to lower subsurface layers
Interceptor Sewer	Large, often flat, sewer built to intercept flows from several trunk sewers
Incipient Motion	Hydraulic conditions which promote the commencement of erosion of a sediment deposit
Invert	Lowest part of the internal surface of a pipe or sewer
Limit of Deposition	Maximum concentration of transported material for given hydraulic conditions without deposition of solids on invert
Loss on Drying	Measure of amount of water lost from a sediment sample when dried to a constant weight in an oven at 105°C
Near Bed Material	Heterogeneous material transported near the bed in sewers, maintains some contact with the invert or sediment bed of a pipe or sewer.
Near Bed Solids	See Near Bed Material
Non-Foul Flush	Storm related flows/samples measured/obtained after the end of the first foul flush
Non-Site Specific	See "site specific"

Non-Volatile Solids	Solids remaining in a sediment sample after furnacing at 550°C for 30 minutes
Particle Size Distribution	Relative proportions of particle size in the ashed residue of a sediment sample measured by sieve analysis
Perceived Class	Sediment classification estimated by visual inspection of sediment characteristics and location
Permissible Canal Velocity	The maximum average velocity for which there is no objectionable scour in the bed of a canal
Pervious Surfaces	See "impervious surfaces"
Pseudo-homogeneous Flow	Particles are transported in turbulent suspension and are uniformly distributed throughout the depth of flow
Re-entrainment	Entrainment of deposited material
Ripples	Small undulations, of saw-tooth profile, which are formed on a deposited bed of sandy sediment.
Saltation	Rolling and sliding motion of particles moving near the bed (mainly river/canal)
Sediment	Accumulations of sewage solids on the bed or sides of sewers or sewer appurtenances
Sediment Classification	A means of differentiating sewer sediments which display varying characteristics
Site-Specific	Pertaining only to one specific sewer location
Soffit	Highest part of the internal surface of a pipe or sewer
Storm Event	Hydraulic conditions associated with significant amounts of rainfall on a sewer catchment
Storm Flow	Sewage flowrates associated with significant amounts of rainfall on a sewer catchment
Stormwater Overflows	See "combined sewer overflows"
Suspended Solids	Solid material transported in overlying water/sewage as opposed to near bed material (see also wash load)
Time Since Start of Storm	The time elapsed since a storm commenced in relation to the time at which a particular sewage sample was obtained

Total Solids	Mass of material remaining in a sediment sample (expressed in relation to original mass of sample) after drying at 105°C in an oven
Total Suspended Solids	Material in suspension in sewage, measured by filtration
Volatile Solids	See "non-volatile solids"
Volumetric Concentration	Concentration expressed in terms of relative volume
Wash Load	Particles are transported in turbulent suspension and are uniformly distributed through the depth of flow

Notation

a	Event specific foul flush parameter, Saget et al.(1995)
a	Site specific constant, Stotz & Krauth (1994)
A	Cross sectional area of flow
A_d	Cross section of dune
A_{gr}	Value of F_{gr} at the threshold of movement
B	Surface width
c	Sediment concentration
C_D	Drag coefficient for a submerged particle
C_L	Lift coefficient for a submerged particle
C_v	Volumetric sediment concentration
C_{vd}	Volumetric transport concentration over dunes
d	Particle "diameter"
d_i	Particle "diameter" of fraction i
d"	Particle "diameter" (imperial units)
$\hat{d}$	Estimated particle size
d_{50}	Median particle size (BS 1337)
D	Pipe diameter
D_{gr}	Non-dimensional grain size
D_r	Rainfall depth
D_*	Particle number, after van Rijn (1984)
e	Voids ratio
E	Erosion rate, after Torfs (1995)
E_m	Erosion rate constant, after Torfs (1995)
f	Transport parameter for limit of deposition, after May (1993)
F_D	Drag force exerted on a particle by a flow
F_G	Force generated by the submerged weight of a particle
F_{gr}	Mobility parameter, after Ackers & White (1973)
F_L	Lift force exerted on a particle by a flow
F_r	Froude number
F_s	Mobility parameter, after May (1993)
g	Gravitational constant
g_s	Transport rate per unit width per unit time

g'_s	Buoyant weight transport rate per unit width per unit time
G_{gr}	Transport parameter, after Ackers & White (1973)
G_s	Mobility parameter
H	Parameter in Ackers-White methodology (Ackers & White, 1973)
I	Hydraulic gradient
I	Maximum rainfall intensity
J	Transport parameter, after Ackers (1991)
J_m	Mean jump length
k	Linear roughness height
k	Time coefficient, Stotz & Krauth (1984)
k_c	Overall equivalent sand roughness with sediment
k_o	Clear water equivalent sand roughness of rigid bed
k_{sb}	Bed equivalent sand roughness with sediment
K	Transport parameter, after Ackers (1991)
L	Length of pipe
m	Moisture content
m	Parameter in Ackers-White methodology (Ackers & White, 1973)
M	Sediment transport rate at $\tau_a = \tau_c$, Ashley et al. (1995)
n	Parameter in Ackers-White methodology (Ackers & White, 1973)
p_i	Fraction of size mass *i* in total mass.
P	Wetted perimeter
P_d	Wetted perimeter of sediment bed
P_o	Wetted perimeter without sediment
q	Discharge per unit width
q_b	Sediment transport rate per unit width, after Einstein (1948)
q_c	Critical discharge per unit width at which movement begins, after Shulits (1934)
$q^*_{s,i}$	The unit-width bed-load transport rate capacity under equilibrium conditions
Q	Discharge
Q_{max}	Maximum discharge in an average DWF day.
Q_s	Volumetric sediment discharge
Q_{s*}	Dimensionless sediment discharge
R	Hydraulic radius

R_b	Hydraulic radius of deposited bed
R_*	Shear Reynolds number
R_{*c}	Value of R_* using a composite friction factor
s	Specific gravity
$\check{S}$	The proportion of the total solids in transport which are in transport at the bed
$\check{S}_B$	The proportion of the total BOD_5 in transport which are in transport at the bed
$\check{S}_C$	The proportion of the total COD in transport which are in transport at the bed
$\check{S}_A$	The proportion of the total ammonia in transport which are in transport at the bed
S_o	Invert gradient
t_r	Relative bed thickness
u_b	Velocity of overtaken base flow
u_s	Mean velocity of storm flow
u_w	Velocity of overtaken baseflow
u_*	Shear stress velocity
u_{*cr}	Critical shear stress velocity
v	Flow velocity
V	Mean flow velocity
V_b	Velocity at the bed
V_{cd}	Critical deposition velocity
V_{cs}	Critical scour velocity
V_L	Limiting flow velocity without deposition
V_m	Minimum head loss velocity
V_{max}	Maximum velocity in an average DWF day
V_s	Self cleansing velocity
V_t	Threshold velocity
$\tilde{w}$	Vertical turbulence intensity
w'	Vertical flow velocity fluctuation
w_s	Particle settling velocity
W_b	Bed width
W_e	Effective bed width
x	ADWP, Stotz and Krauth (1984)

y	Amount of washout material, Stotz and Krauth (1984)
y	Vertical distance above invert
y_s	Mean sediment bed depth
y'_s	Depth of weak surficial sediment layer, Ashley et al. (1995)
y_e	Erodible bed depth, after Wotherspoon (1994)
y_{max}	Maximum depth in an average DWF day.
y_o	Flow depth
Z	Volume of deposited sediment
α	Coefficient, after Lin and Le Guennec (1995)
α	Coefficient, after Torfs (1995)
α	Transport parameter, after Ackers & White (1973)
β	Transport parameter, after Ackers & White (1973)
δ	Transport parameter, after Ackers & White (1973)
ε	Transport parameter, after Ackers & White (1973)
γ	Transport parameter, after Ackers & White (1973)
γ	Unit weight
η	Transport parameter, after May (1993)
κ	von Karmen constant
λ	Friction coefficient
λ_b	Value of λ for bed shear stress
λ_c	Composite value of λ for a conduit with sediment
λ_g	Value of λ for grain shear stress
λ_o	Value of λ for clean pipe
ν	Kinematic viscosity
θ_{cr}	Critical mobility number, after van Rijn (1984)
θ	Transition factor, after May (1993)
$\overline{\rho_o}$	Initial average bed density, after Wotherspoon (1994)
ρ_d	Sediment dry density
ρ_e	Erodible sediment density
ρ_s	Sediment density
ρ_w	Fluid density
τ_*	Non dimensional shear stress, after Shields (1936)
τ_{*c}	Non dimensional critical shear stress, after Shields (1936)

τ_a	Applied shear stress
τ_c	Critical boundary shear stress
τ_{cs}	Yield stress of surface sediment layer, after Ashley, et al. (1995)
τ_{cu}	Yield stress of underlying sediment layer, after Ashley, et al. (1995)
τ_o	Boundary shear stress
τ_y	Yield shear stress
ξ	Dimensionless coefficient which controls density
ζ	Dimensionless coefficient which controls erodibility
Φ_b	Transport parameter, after Einstein (1950)
Θ_g	Mobility parameter, after Einstein (1950)
Ψ	Coefficient, after Du Boys (1879) and Straub (1935)
Ψ_b	Flow parameter
Ω	Transport parameter for limit of deposition, after May (1993)
ϵ_s	Turbulent diffusion coefficient, after Schmidt (1925).

List of Abbreviations

ADWP	Antecedent Dry Weather Period
AVG	Average
BOD	Biochemical Oxygen Demand
BOD_5	Five Day Biochemical Oxygen Demand
BSI	British Standards Institute
CALC	Calculated
CIRIA	Construction Industry Research and Information Association
COD	Chemical Oxygen Demand
CSO	Combined Sewer Overflow
DAS	Diameter-Area-Slope Factor
DIT	Dundee Institute of Technology
DWF	Dry Weather Flow
EPSRC	Engineering & Physical Sciences Research Council
FFF	First Foul Flush
ID	Internal Diameter
$LOAD_{ff}$	Pollutant Load Carried by a Foul Flush
LOD	Loss on Drying
MAX	Maximum
MIN	Minimum
NBS	Near Bed Solids
NH4	Ammonia
OBS	Observed
$RINT_{max}$	Maximum Rainfall Intensity
PPM	Parts Per Million
PSD	Particle Size Distribution
SERC	Science & Engineering Research Council
SD	Standard Deviation
SS	Suspended Solids
SV	Settling Velocity
STDURN	Storm Duration
TRC	Tayside Regional Council
TS	Total Solids
TSS	Total Suspended Solids
TSSS	Time Since the Start of Storm
UAD	University of Abertay Dundee
UPM	Urban Pollution Management Programme
WRc	Water Research Centre
WWTC	Wastewater Technology Centre

Chapter 1 : Introduction

1.1 Background

It is the purpose of combined sewerage systems to transport domestic, industrial and storm solids, and associated liquid wastes, for treatment and disposal. However, the movement of solids in sewers has come under increased scrutiny in recent years, due to pollution concerns related to this material. The biochemical and aesthetic impacts of sewage spills into the environment, via CSO structures and overloaded treatment plants, has heightened public awareness of the perceived problems.

As well as pollution implications, the presence of sediments in sewers causes hydraulic overloading, and often premature activation of combined sewer overflows. In recent years an extensive programme of laboratory based work has been undertaken in the U.K. (Nalluri & Alvarez, 1992, Ab. Ghani, 1993, May, 1994 and Ackers et al., 1994) investigating the transport of solids in sewerage systems, with the aim of reassessing the current sewer design methodology. However, these studies have produced empirical and semi-deterministic models which have been concerned primarily with the hydraulic problems caused by sewer sediments, and often do not represent the range of material found in transport in sewers, or the characteristics of the sewers themselves (Ab. Ghani, 1993). Additionally, in the development of these models, no reference is made to the pollutant potential of the material in transport.

Existing laboratory and field based research exercises have focused on the relatively small, discrete particles associated with solids transport in sewers. It is clear, however, that combined sewer systems have sanitary inputs which are known to comprise of a significant proportion of large organic solids, as well as finer particles. From the limited studies undertaken to date (Crabtree et al., 1994 and Ashley & Verbanck, 1996), it is apparent that these larger solids are important, not just for CSO discharges, but for their interaction with sediment deposits, the deposition process, erosion behaviour, deposit breakdown and the contribution to first flush phenomena. The increased concern regarding CSO spills into the environment has fuelled the development of sewer flow quality models such as HYDROWORKS DM and MOUSETRAP (Crabtree et al., 1993).

Based on observations in UK sewerage systems, and further afield (Ashley & Verbanck, 1996) three principal modes of solids transport have been established, although the nature of each mode may be dependent on site specific characteristics:

- Suspension
- Near the bed as "bed-load"

- Semi-permanent deposits

In addition to these three modes of transport, where deposited sediments are non-cohesive sands, it is possible to consider any bed forms as a mode of transport, as they have been shown to creep slowly along the invert (England & Hansen, 1967 and Kleijwegt, 1992a).

Of these modes of transport, that which has been given increasing importance (Ab Ghani, 1993, Ackers et al., 1994 and Ashley & Verbanck, 1996) is the transport of material at the bed. This is due to the heterogeneous nature of this material, and often intense pollutant concentrations, when compared with the suspended mode of transport. Recently this material has been considered to be of some importance, principally due to its association with first foul flushes in sewers and the ease with which it is eroded. It is often composed of large organic (gross) solids. It is also promoted as a source of the inorganic material which form sediment deposits (Lin et al, 1993a &b, Bertrand-Krajewski, et al., 1995 and Ashley & Verbanck, 1996).

1.2 Scope of Present Research Programme

It is the aim of the current study to investigate the nature of solids in transport in combined sewerage systems in general. However, special consideration is given to the material in transport at the bed due to the perceived high pollutant potential of this material in general. The specific aims of this project, in terms of data collection and analysis, can be summarised as follows:

1. Establish a methodology which can be used to obtain representative samples of the material moving at the bed of sewers in Dundee, and conceivably further afield.
2. Characterise the physical and biochemical characteristics of the material in transport at the bed of combined sewers.
3. Establish a methodology which could be used to give an estimation of the material in transport at the bed of combined sewers, within a reasonable degree of accuracy.
4. Attempt to link the material in transport at the bed with the pollutant potential of foul flush phenomena experienced in some sewers.

In attempting to meet these aims the following objectives were sought:

1. Compare the material in transport at different points in the sewerage system.
2. Highlight any spatial or temporal variability in the nature of the material in transport.
3. Compare the mass of material in transport at the bed with other modes of sediment transport in sewers.

4. Evaluate the performance of contemporary bed-load transport models when applied to real sewer sediments.

It is anticipated that the research presented in this thesis will be utilised to augment the data and knowledge used to construct the next generation of sewer flow quality models.

All the data presented in this study were collected wholly in the Dundee combined sewerage system. At the outset it should be recognised that the Dundee sewerage system is not necessarily representative of sewerage systems in the U.K. as a whole.

1.3 Thesis Structure

Including this chapter, this thesis consists of 8 chapters and 10 appendices. Chapters 2, 3 and 4 give a review of the current knowledge dealing with the movement of sediments in sewers. As this study has been field work based the review of literature discusses important field based observations and relates them to data historically collected in Dundee. In addition, the literature review gives a review of contemporary laboratory based work undertaken in this field, as much of the work will be applied to the data collected.

Chapter 2 gives an overview of sewer sediment research, and relates current knowledge to classical transport work in rivers and estuaries. Chapter 3 goes on to examine in detail each of the ongoing related field based studies, these studies are examined in relative isolation due to the large differences in observed materials and analysis techniques. Much of the problems associated with sewer sediments specifically are highlighted in Chapter 3. As this study has used recent advances in laboratory based sewer sediments research in the UK, and further afield, Chapter 4 gives an overview of the principal advancements and discusses the limitations of these results.

An overview of the characteristics of the Dundee sewerage system is given in Chapter 5, which also discusses study site selection and data collection methods employed as part of this project, along with data collection priorities.

Chapter 6 assesses the data collected, and gives general observations and results relating to near bed solids characteristics, and pollutant potential. The importance of the material transported at the bed, in comparison with other modes of transport, is highlighted, along with the role of this material in the first foul flush phenomena.

The rate of transport near the bed is addressed specifically in Chapter 7. Contemporary bed-load transport models are evaluated, and the results are analysed. The development of a novel method for the determination of near bed solids transport rates at each of the study sites is described.

In Chapter 8 conclusions are drawn regarding the analysis of the data collected as a part of this study. The conclusions are discussed, and recommendations are made regarding future research.

A full list of the reference material on which this study has relied is given in the reference section.

All relevant figures and tables are given in the text where possible, however, for brevity, a proportion of the figures and tables, which are not essential to the flow of this thesis, may be found in the appendices.

1.3.1 Authors Note

One of the main aims of this study was to obtain a methodology which may be used to estimate the near bed solids transport rate in a live sewer. However, it is the norm in sediment transport studies, to express sediment transport relationships in terms of a transport concentration. The two terms are not interchangeable, although it is a matter of simple arithmetic to covert between the two parameters.

Over the 48 month duration of this project, there have been many changes in higher education establishments in the U.K., and in the management of water distribution and sewage management provision. Although this has had little direct affect on the progress in this study, the names of some of the interested parties have changed. At the initiation of this study, the project was part of the sewer sediments research programme undertaken by;

Wastewater Research Group
Department of Civil Engineering, Surveying and Building
Dundee Institute of Technology

However over the 48 months duration of this study this has now evolved to:

Wastewater Technology Centre
Division of Environmental Engineering
School of Construction and the Environment
University of Abertay Dundee

Additionally from the 1st April 1996, the responsibility of sewerage management in Dundee, and water supply, has been transferred from Tayside Regional Council Department of Water Services to North of Scotland Water Authority.

Chapter 2 : Sewers Sediments - Overview

There has been a considerable amount of research investigating sediment transport in streams, rivers, estuaries, channels and, more recently, sewers. This chapter aims to bring together much of the work in this field. This chapter relates relevant classical sediment transport research to the current knowledge concerning sewer solids. The work reported here will be restricted to the work applicable to sediment transport in channels in general, and sewers in particular, and the large mass of work relating to sediment transport in rivers and estuaries will only be touched upon where directly relevant.

Due to the nature of data collection in live sewers, and the variations in the materials in transport due to factors specific to a single catchment and/or country, only an overview of the results and observations made in the field is given in this chapter. Whilst each of the main internationally renowned data collection exercises are dealt with in relative isolation in Chapter 3, and laboratory studies are reported in Chapter 4.

Special importance is given to fieldwork undertaken in the Dundee system sites as, in many cases, the data collected in this study were obtained from the same locations. Additionally, the results collected in Dundee previously have provided the background to this study.

2.1 Introduction

Sewer sediment can be considered as being any type of settleable material found in combined, foul or storm water sewers, and associated structures. It is the function of sewers to transport sediment for treatment and disposal, along with the associated liquid waste.

Sediment deposits have always been present in sewers (CIRIA, 1986). Traditionally, the problems associated with the presence of sewer sediments are perceived to be hydraulic in nature, usually taking the form of a reduction in the sectional area (Broeker, 1984, Ashley et al., 1992 and Dinkelacker, 1992), and increased hydraulic roughness of the pipe (Butler et al., 1996a), which in turn can lead to a decrease in the overall capacity of the sewer. In recent years an increase in impervious areas, due to urbanisation (CIRIA, 1986 and Novak & Nalluri, 1987), coupled with the concern given to water quality in rivers, has meant that the amount of pollutants associated with sediments has been given increased attention. Pollution usually occurs when sewers discharge sediments into rivers, and other receiving waters, via combined sewer overflows (CSOs) or outfalls (Ellis, 1977, McGregor et al., 1993, Crabtree et al., 1994, Crabtree et al., 1995 and Gent et al., 1995), or where hydraulic overloading causes flooding.

An investigation in 1986 (CIRIA, 1986) of the United Kingdom's 235,000km sewerage system indicated that some 25,000km suffered from sedimentation. Lindholm (1984), in an investigation of four Norwegian towns and cities, estimated that sediment deposition represented 12-72% of the annual domestic solid waste discharged into the sewerage system.

In addition to domestic and industrial inputs, the main source of solids in sewerage systems originate from surface run-off from catchments (Ashley & Crabtree, 1992, Xanthopoulos & Augustin, 1992). The UK based review of sediments in sewers (CIRIA, 1986) established a list of sources of sewers sediments, as perceived by system operators;

- Road surface materials
- Material from road works
- Motor vehicles
- Washoff from adjacent areas
- Construction work; stockpiles and spillages
- Industrial and commercial activity
- Litter
- Vegetation
- Foul sewage
- Sewer structure decay
- Ingress of soils from pipes, manholes, gullies, etc.
- Roofs
- Atmospheric fall-out

The degree to which each of the above factors contributes to the mass of sediment in sewers will largely be dependent on catchment characteristics (land use, location, etc.) and street and gully cleaning routines (Ellis, 1986). The movement of solids through sewer systems is as idealised in Figure 1.

Sewerage systems which are prone to sedimentation problems are, typically, those which drain flat or mildly sloping catchments (Bachoc, 1991 and Ashley & Crabtree, 1992), and also those which have a large proportion of combined sewers, due to their variations in daily flow conditions. Due to the variable nature of flow in sewers it is almost impossible to prevent sediment deposition throughout the DWF pattern.

However, a well designed, and managed, system will frequently attain a flow sufficient to remove any sediment which has accumulated to further down the sewerage system, if not out of it totally.

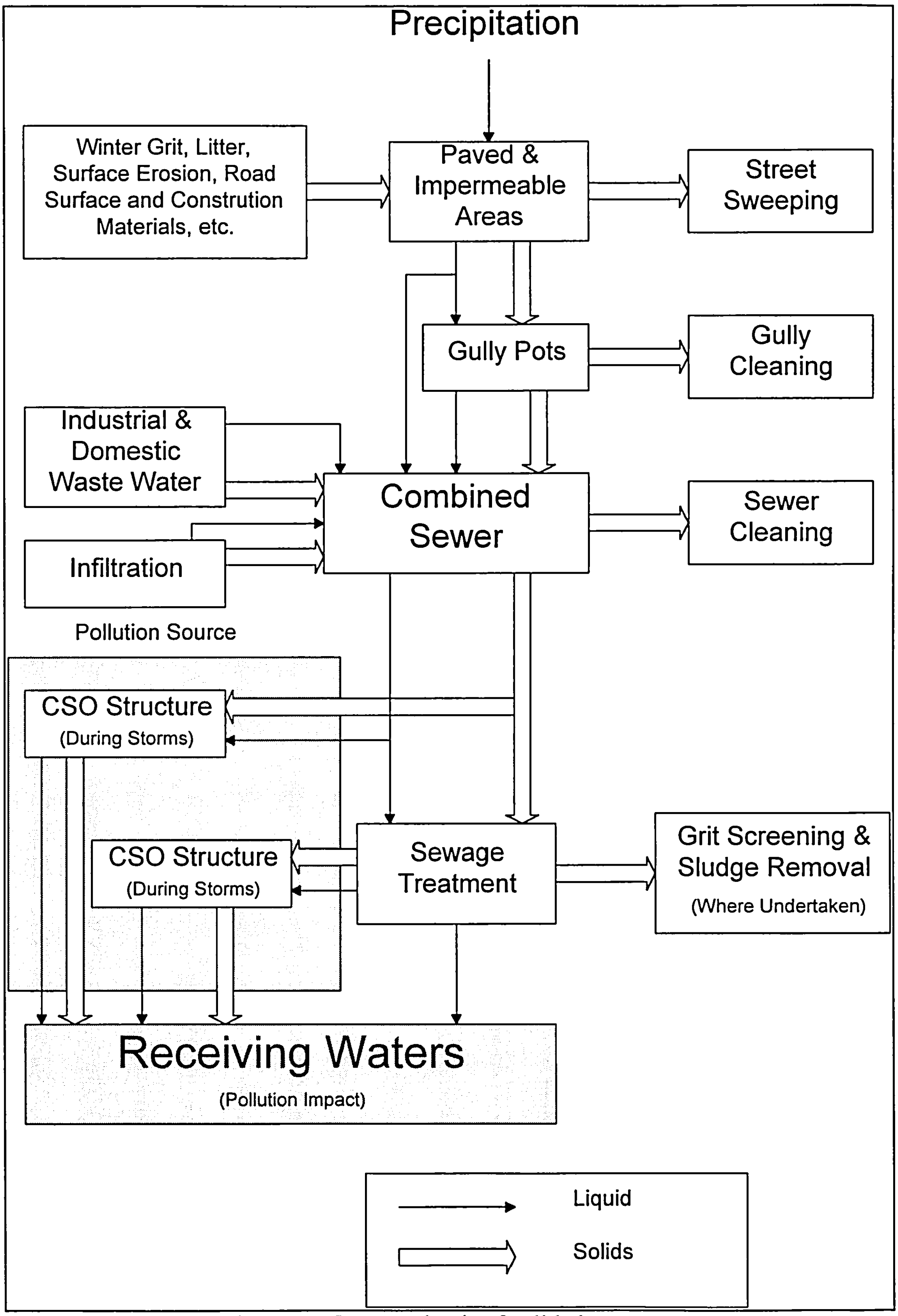

Figure 1 : Entry and exit of solids in sewers
(adapted from Shen, 1981 and Butler & Clark, 1995)

The presence of sediment in a sewer does not necessarily indicate a problem, however difficulties do occur when the sediment impedes the flow. Problems also arise when the sediments encourage the in-sewer build-up of organic and related pollutants (Ashley & Crabtree, 1992). These accumulations usually consist of a mobile sludge deposit lying on top of primarily inorganic coarse-grained materials. When velocities increase during storm events the former material will erode quickly as the shear stress along the bed increases, and account for much of the pollutants associated with the first flush phenomena (Gieger, 1984 & 1987).

Where sediment deposition does occur two possible situations have been observed in the field and in laboratory studies (Nalluri & Dabrowski, 1994, Butler et al., 1995a);

- The reduction in velocity may cause a reduction in the sediment transport capacity of the flow and lead to further deposition in the sewer, and upstream. Ultimately, the depth of deposit will become sufficient to increase the flow depth until an equilibrium condition is reached. Due to the resultant increased pressure the transport capacity of the flow is increased until a surcharged condition is reached. Ultimately a condition will be reached were the sediment flux into and out of the system is balanced. Although this situation may be tolerable, to some extent, during DWF conditions, during storm events such a conduit would have an increased liability to cause surface flooding.
- The presence of a sediment bed may allow the flow to acquire a greater capacity for transporting sediment (Ab. Ghani, 1993), which may more than compensate for the reduction in velocity caused by the bed roughness. The increase in bed width and related increased ambient sediment transport capacity conditions may reach an equilibrium condition, when no long term increase in the sediment bed depth is observed. Work undertaken in France (Laplace et al., 1990 & 1992) indicated that the profile of sediment deposits tends to increase the bed gradient with time to balance the transport of solids. Whilst this condition may be tolerable during DWF, the sewer sediment will act as pollutant store which may be eroded during storm conditions.

The transportation and deposition of sediment in sewers and watercourses is a complex subject (Yalin, 1977, Hallermeier, 1982, Ashley et al., 1992 and Bertrand-Krajewski et al., 1993), mainly due to the variety of ways in which the sediment and flow interact. Where deposits do not exist on the invert a sediment particle may travel for some length in suspension or as bed-load over a relatively smooth surface. However, if deposits do exist the sediment will be transported over a surface which is rough and potentially mobile, by a flow affected by these characteristics. This is due to the presence of the deposits which increase the surface roughness at the bed, increasing the drag, this in turn increasing the energy lost by the flow over the length of sewer considered.

2.2 Flows

The most important factors which affect the movement of a sediment particle through any sewer are related to the characteristics of the flow which that system conveys. By nature, the flow in a sewerage system can be described as transient, with frequent low and occasional high discharge conditions. Typically, flows in a combined sewer may vary from an average dry weather flow to a one in two year storm event, which may result in surcharging of the system. Additionally, DWF discharges will vary continuously on a micro and macro scale.

Storm events provide full-pipe conditions typically on a once in two year basis (CIRIA, 1986), the resulting runoff produces bulk sediment movement, affecting deposits in several ways, most of which are velocity dependent. The following velocity conditions which affect sediment movement have been identified (May, 1982):

Threshold velocity V_t - the average flow velocity at which isolated particles just start to move.

Critical deposit velocity V_{cd} - the average flow velocity below which particles on the pipe invert start to form stationary deposits.

Critical scour velocity V_{cs} - the average flow velocity required to scour a deposited bed.

Minimum head-loss velocity V_m - the average flow velocity which will transport a given concentration of sediment with the minimum possible head-loss.

Self-cleansing velocity V_s - the average flow velocity above which all the particles are transported by fluid forces rather than by forces transmitted between particles.

The absolute values of these parameters will vary considerably depending on sediment shape, size and the physical characteristics of the conduit concerned.

The movement of a suspended particle through a sewerage system essentially consists of three phases (van Rijn, 1982a), which may be repeated several times. These phases consist of: entrainment; transportation; and deposition. Thus the sediment transport process can be described as intermittent.

Entrainment is the process whereby sediment is 'picked up' by the flow, and can only occur when the lift and drag forces exerted by the flow exceed the restoring forces on the particle. For non-cohesive materials the restoring forces consist of the submerged weight, and any interlocking between adjacent particles. In sewers cohesive-*like* bonding may develop between finer particles, in addition to cementation and agglutination under certain chemical and biological conditions.

The flow regime within a sewer conduit is typically turbulent, with the more exposed particles creating wakes, resulting in a pressure difference, and resultant lift force across the individual grains. This pressure difference will tend to erode the sediment from the bed, depending on the intensity of the turbulence and the bed structure. Hence a critical erosion velocity or bed shear stress (τ_0) is often utilised to estimate the onset of erosion (Du Boys, 1879), and possible entrainment. The relationship between these two parameters is illustrated in equation 1;

$$\tau_o = \frac{\lambda}{8}\rho_w v^2 \qquad \text{...1}$$

A sediment particle on the fluid/bed boundary will experience a drag force, generated by its exposure to the moving fluid. The force can be estimated by using equation 2;

$$F_D = \frac{\rho_w C_D A v^2}{2} \qquad \text{...2}$$

The same particle will also experience lift forces, which are often ignored in sediment transport theory (Loveless, 1986), created by the distortion it causes in the surrounding flow field. The lift forces can be estimated using equation 3;

$$F_L = \frac{\rho_w C_L A v^2}{2} \qquad \text{...3}$$

If the ambient velocity (and hence shear stress) is slowly increased there will come a point where the combined lift and drag forces exceed the force generated by the particle submerged weight, F_G, (equation 4) and the particle will be dislodged from the bed. This condition is termed *the threshold of grain movement* (Raudkivi, 1990).

$$F_G = \frac{(\rho_s - \rho_w)\pi g d^3}{6} \qquad \text{...4}$$

Research in the past (Shields, 1936) has reasoned that particle entrainment is related to Reynolds Number. When Reynolds number is estimated, however, conditions at the bed should be taken into account rather than that of the average flow conditions as this will better represent the process of sediment transport in the near bed region.

After particle movement has been initiated, the hydrodynamic forces acting on a particle are altered by its separation from the sediment bed. If the flow is steady, conditions will not dramatically change, and it is likely that the movement will essentially take the form of a rolling action along the bed of the sewer, or, if there is sufficient energy in the flow then the particle will be entrained and will be retained in the flow. The retention of a particle in a flow is dependent on the relationship u_*/w_S (Raudkivi, 1990), the ratio of the intensity of the vertical velocity turbulence to settling velocity and is based on the work of Schmidt (1925) and O'Brien (1933), equation 5;

$$w_s c + \epsilon_s \frac{dc}{dy} = 0 \qquad \text{...5}$$

Deposits on the bed of a conduit are subjected to relatively steady flows and the entrainment of particles is largely as described above (Raudkivi, 1990). This work is important as the ratio u_*/w_S is used by several researchers (e.g. Butler et al, 1996a & b) to mark the separation point between bed-load and suspended transport (see section 2.4).

2.3 Sediment Characteristics

The most comprehensive and co-ordinated field studies of sewer sediments have been those undertaken in the UK, (Crabtree et al.,1991, Ashley & Crabtree, 1992, Ashley et al., 1992b, Wotherspoon, 1994, and Gent et al., 1995), Belgium (Verbanck, 1992 and Torfs, 1995) and in France (Chebbo et al., 1990, Bachoc, 1991, Laplace et al., 1990 & 1992, Lin et al., 1993a & b and Bertrand-Krajewski et al., 1995). Early studies carried out in Germany and Scandinavia only reported limited assessments of in-sewer deposit characteristics, usually based on flushing studies of small sized collector sewers (e.g. Larson et al., 1990). Such studies dealt primarily with assessments of the extent of deposition within systems and the polluting consequences of storm flow wash-out, rather than the nature of the deposits. Important studies designed to assess the shear resistance of in-sewer sediments have been reported from Germany, as part of studies of sediment characteristics and deposition in Hanover (Ristenpart, 1995), as well as in the U.K. (Williams et al., 1989, Crabtree, 1989 and Wotherspoon, 1994).

Sewer sediment characteristics can be described in terms of both individual particulates or, more practically, as bulk properties. The continuously varying hydraulic and boundary conditions in the sewers, together with the nature of the inputs, control the type of material which is deposited, transported or eroded at a given location. Crabtree (1989), based on limited data from UK sewers, proposed a sediment classification methodology for engineers in the field based on four primary classes A, C, D, E, with a fifth class, B, comprising agglutinated or cemented Class A material. A summary of the definition of each sediment class is given in Table 1 and is illustrated in Figure 2.

The large organic fraction found in Classes C and D (an average of 50 and 61% respectively), indicates that these sediments differ markedly from conventional engineering conception of 'sediments' found along pipe inverts. The clear distinction implied by these Classes is not so apparent in reality, as sediments are usually mixed between these class types as illustrated in Table 2 (Ashley et al., 1989 and Ashley et al., 1992b). There is also some uncertainty as to where the boundary definition between a deposited sediment and the material transported as 'bed-load' lies (Ashley and Verbanck, 1996). The Class C sediment defined above may be a true sediment only in stagnant zones (Ackers et al., 1994) as it offers only minimal resistance to shear.

TABLE 1 : SEWER SEDIMENT TAXONOMY AS PROPOSED FOR UK USAGE (Crabtree, 1989 and Crabtree & Clifforde, 1990)

	Description/ where found	Bulk S.G.	% by inorganic particle size (mm) minimum-mean-maximum			Yield Strength (N/m^2)	Organic Content (%)
			<0.063	0.063-2.0	2.0-50.0		
A	Coarse, inorganic bed material - widespread	1.72	1-6-30	3-61-87	3-33-90	>400	7.0
B	As A but cemented by the addition of fat, bitumen, cement, etc. into a solid mass	N/A	N/A	N/A	N/A	>800	50.0
C	Mobile, fine grained found in slack zones, in isolation of overlying Type A	1.17	29-45-73	5-55-71	0	98 (AVG)	50.0
D	Organic pipe wall slimes and zoogleal biofilms around mean flow level	1.21	17-32-52	1-62-83	1-6-20	N/A	61.0
E	Fine grained mineral and organic material found in CSO storage tanks	1.46	1-22-80	1-69-85	4-9-80	25 - 200	22.0

The sediments found in different parts of a combined sewer network will have differing characteristics (Bachoc, 1992, Ashley, 1993 and Wotherspoon, 1994), as described in Table 3, this being primarily due to differences in the characteristics of the catchments and inputs. In general, the larger and denser particles will be found near the head of sewers, with the finer particles in the downstream parts of the systems (Bachoc, 1992). The particle sizes for the inorganic materials encountered in sewers around Dundee are illustrated in Figure 3 (from Ashley et al., 1990).

TABLE 2 : PARTICLE CHARACTERISTICS IN DUNDEE SEDIMENTS, AS PERCEIVED WITH MIXED DEPOSITS

		Perceived Class			
Particle characteristic		1: A	2: A/C	3: C/A	4: C
Vol. solids	Max.	3.4	10	17.6	5
(%)	Min	0.2	0.2	0.5	4
D10	Max.	0.4	0.2	0.4	0.2
(mm)	Min	0.05	0.01	0.01	0.1
D50	Max.	2.1	1.3	0.7	0.9
(mm)	Min	0.55	0.2	0.09	0.8

TABLE 3 : DEPOSITION OF SEDIMENTS IN COMBINED SEWERS

Sewer type	Location of deposits	Nature of deposits
Collector Sewers	At discontinuities*, otherwise randomly located in discrete 'lumps'	Large organics, sand and gravel
Trunk Sewers	At discontinuities*, Otherwise only larger, denser particles deposited	Large granular particles, some intermixed (large) organics
Interceptor Sewers	At discontinuities*, otherwise where gradients slack	Fewer large organics than above, plus finer inorganic particles than above

* structural or hydraulic discontinuities

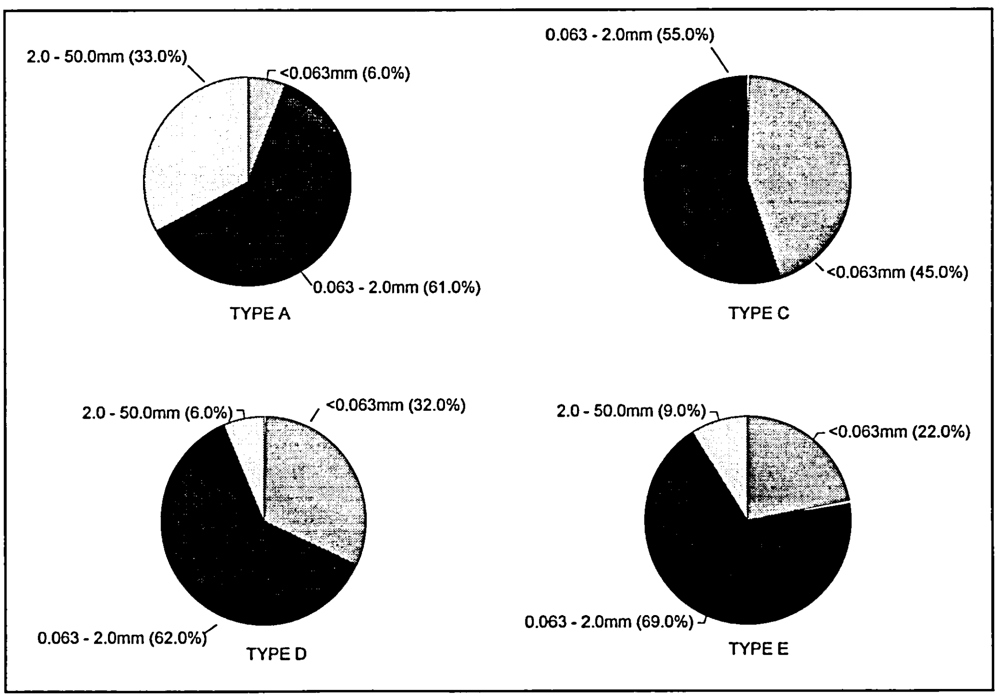

Figure 2 : Sediment Taxonomy - Particle Size Ranges as Proposed for UK Usage (adapted from Crabtree, 1989)

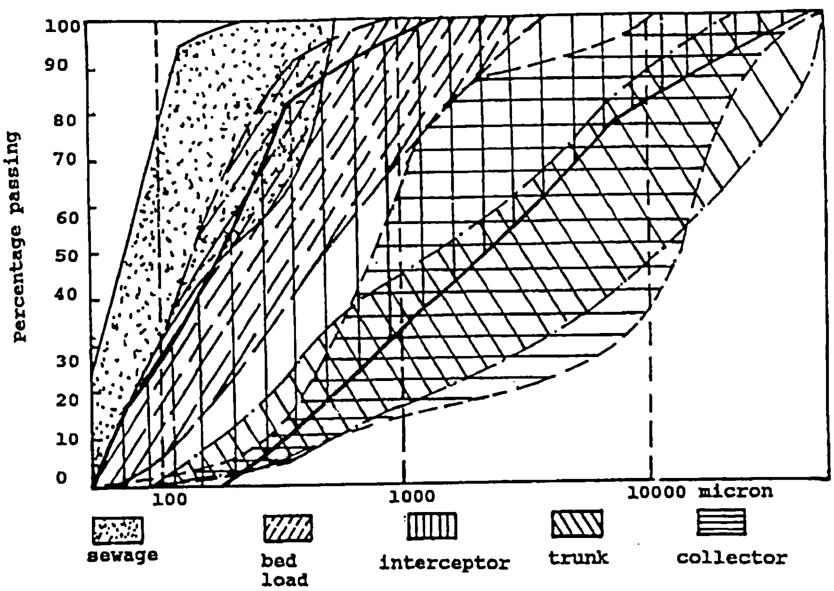

Figure 3 : Sewer sediment particle size distributions - Dundee and UK data
(from Ashley et al., 1990)

The Dundee main sewer deposits may be compared with French, German and Belgian results, as illustrated in Figure 4, from Ashley & Crabtree (1992).

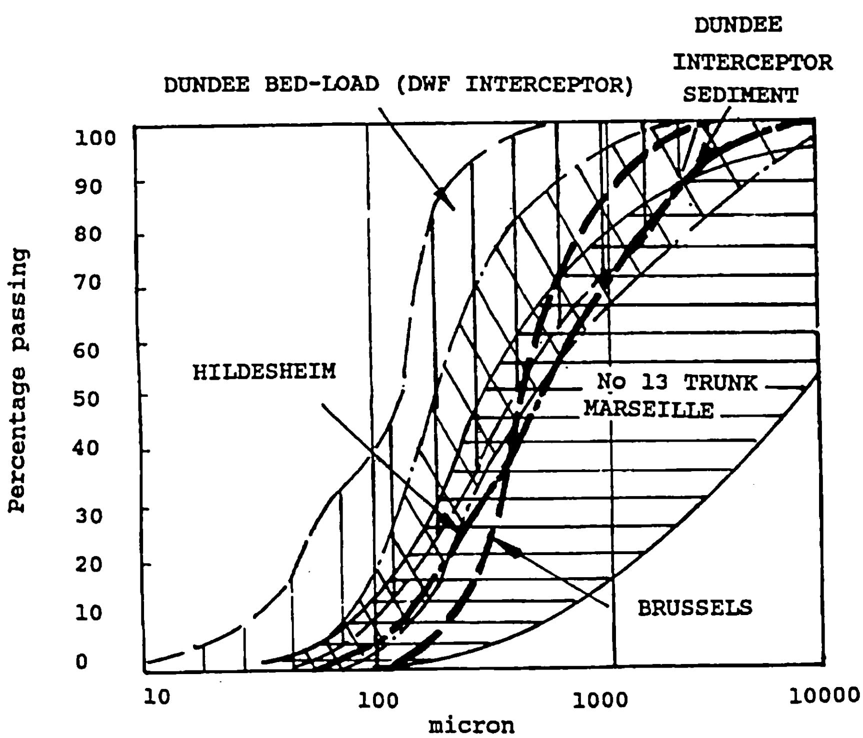

Figure 4 : Sewer sediment particle size -
Dundee, Marseille, Hildesheim & Brussels
(from Ashley & Crabtree, 1990)

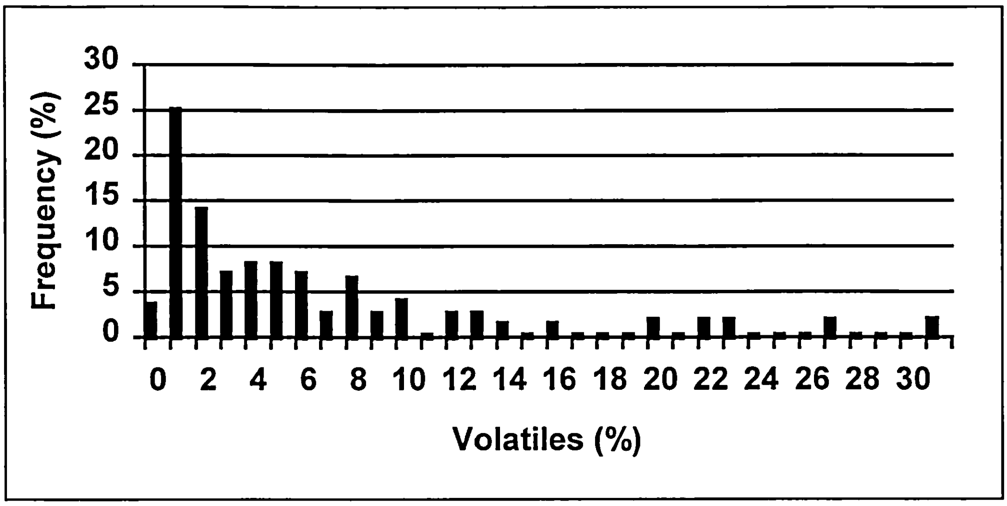

Figure 5 - Sewer sediments in Brussels from a variety of sources - volatile (organic) frequency distribution (from Ashley and Verbanck, 1996)

The sediment particle size ranges observed for the various French sites (Chebbo et al., 1990 and Bachoc, 1992) are summarised in Table 4, together with sewage particulate data, and reported data for Brussels from Verbanck (1990 & 1992) and ranges for the UK are also given. It should be noted that the particle size of the smallest fraction <63μm has in each case been determined indirectly by settling velocity determination. In view of the uncertainties surrounding this practice these results should be treated with some caution. The Belgian data are reportedly for samples with a small volatile (<5%) fraction, although the volatile content of each particle size (sieve) class was found to increase with decreasing particle size, and the overall frequency distribution of volatile fraction is shown in Figure 5. The UK data are for samples with organic contents from about 3% up to 96%, depending upon the WRc classification. Generally, the Class A sediments are those which are most inorganic, and the French and Belgian sediments appear to correspond with this type.

TABLE 4 : PARTICLE SIZE RANGES - SEWER SEDIMENTS

		Particle Size				
Country	Sewer Type	<63μm	0.063μm -0.2	0.2-2	2-20	>20
France	Man-entry 'upstream' sewer	2%	8-10%	23-60%	25-47%	7-18%
	Trunk sewers	4%	5-10%	38-55%	25-45%	8-10%
	Interceptor sewer	4.5%	35.5%		60%	
Belgium	Interceptor sewer	3%	17%	78%	2%	NR
	All sewers in Brussels	20%	30%	43%		9%
UK	Interceptor sewer	1-20%	1-21%	32-80	65-20%	NR
	Trunk sewer	1-8%	1%	18-41	41-50%	NR

As part of the French programme a continuous study has been undertaken of the No. 13 trunk sewer in Marseille which has shown a gradual sediment build-up following cleaning. The Marseille data (Laplace et al., 1990 & 1992) show an 'evolution' of particle sizes temporally and spatially. Initially, the sediments dispersed along the sewer length were of relatively uniform size, but these were observed over the course of a year to become more graded as the bed developed. Near the head of the 2.75 m high sewer the d_{50} of the bed particles gradually increased from 2mm up to approximately 8mm, with smaller particles (<2mm) predominating near the end of the studied sewer. No significant consolidation of the bed was noted, and throughout the study the bed was found to be composed of relatively large particles, with less than 10% having a size of 200μm or less. Although this result may be due to the non-selective nature of gullies used in Marseille (and over the majority of French catchments), this observation is consistent with the results for flushing tests carried out in the USA, where the flush wave apparently 'leached' many of the finer particulates from the bed deposits. During storms in Marseille the particles in suspension 30 cm above the bed were sampled and shown consistently to be predominantly (70%) smaller than 100 μm. These particles had a low d_{50} of 40 μm. Sample preparation using ultrasound dispersion was applied to some of the French samples, the results showed an apparent reduction in particle sizes presumably because of the breakdown of flocculated particle groups. The Brussels study (Verbanck, 1990) also indicated that the finer particulates (<125 μm) were being leached from the sediments by diurnal increases in dry weather flow. The organic content of the sediment throughout the sediment bed, which had a depth of 150 mm, was examined and found to be highest in the deeper layers, and this was hypothesised as being due to 'shielding' by the overlying material preventing washout of the finer (mostly organic) particles.

During sediment studies in Dundee (Ashley et al., 1993, Ashley, 1993 and Wotherspoon, 1994) more than 150 bed samples have been taken from the main interceptor sewer and contributing trunk and collector sewers. The data are for sieved samples following ashing at 550°C and represent only the mineral sample fraction. Coulter Counter analyses of the smaller sized (ashed) fraction were used to further investigate the particulates below 63 microns in size. The d_{50} for the Interceptor sewer sediment samples was found to be in the range 0.2 - 2.0 mm, whereas the Perth Road trunk sewer samples had a d_{50} of 2 - 20 mm. The depth of deposits in the Interceptor sewer averaged 100 - 200mm and approximately 75 mm in the Perth Road trunk sewer. The trunk sewer deposits had an average volatile fraction of about 3%, compared with a range up to 20% in the Interceptor sewer. The average bulk density of the Interceptor deposits was found to be 1580 kg/m^3 compared with 1806 kg/m^3 for the trunk sewer. These figures are comparable with the Brussels figure of 1510 kg/m^3. Recent results from the sewer in Hildesheim in Germany (Ristenpart, 1995) have shown that the characteristics of sediments vary extensively both spatially and temporally. Of note is the ageing of 'fresh' sediments at a point in the interceptor sewer, illustrated by the increase in bulk density from 1200kg/m^3 to 1840kg/m^3 over an (unspecified) period. These observations of coarser, more inorganic, sediments being found in trunk sewers where gradients are steeper than in Interceptors are consistent with the other studies described, and indicative that the finer organic particulates are more likely to deposit and remain in Interceptors with slacker gradients rather than local collector or trunk sewers.

The shear strength characteristics of sediment deposits have been examined in limited French (Laplace et al., 1990) studies, and in more detail for UK studies (Williams et al., 1989, Wotherspoon, 1992) in which disturbed samples have been analysed using applied stress rheometrical techniques. These have revealed that deposits can have an apparent yield strength in excess of 2.5 kN/m^2 (Wotherspoon & Ashley, 1992). However, these tests do not represent the presence of the armoured layer which forms a hardened crust at the top of a sediment deposit due to the elutrition of smaller particles. This observation has also been made by Partheniades and Paaswell (1970) in estuarine studies, additionally Partheniades and Paaswell found that the erodibility of weak clays was not linked to their shear strength, although the same was not true for stronger samples.

In addition to the use of these sophisticated specialist rheometric techniques, a range of standard geotechnical tests have been applied to in-situ sediments in Dundee and in France (Laplace et al., 1990). Vane tests using standard soil testing equipment for Dundee, Marseille and Paris sewers have indicated very similar yield strengths for deposits, with up to 2 - 10 kN/m^2 and 2 - 20 kN/m^2 being measured respectively in Scotland and France, although shear stresses measured in the field do not normally exceed 5-7 N/m^2 (Kleijwegt et al., 1990). The more rigorous rheometrical tests carried out at University College, Swansea on samples taken from the Dundee sewer indicated yield strengths of up to 2.5 kN/m^2 (Williams et al., 1989). The development of a cohesive structure and resistance to shear stresses in sewer sediments is a complex process involving consolidation, chemical and biological interactions and temporal and spatial changes. Many questions remain regarding the development of a bed structure from depositing suspended or bed-load material, and the transition from a fluid to a weak and gradually strengthening 'solid' bed (Ristenpart, 1995). Even in the artificial, but controllable, conditions of a laboratory (Nalluri & Alvarez, 1992, Stotz & Krauth, 1986, Torfs, 1995 and Skipworth et al., 1995) the study of changes in cohesive-*like* sediment beds in response to imposed flow conditions is difficult. How such studies relate to field conditions is not always clear, but a number of conclusions may be made:

- Sewer sediments can have cohesive-*like* properties, but these may not necessarily be because of cohesive forces in the classical sense, which are caused by electrostatic attraction - in sewers the effect is usually produced by chemical and biological agglutination (Williams et al., 1989 and Wotherspoon & Ashley, 1992).
- The structure of sewer sediments very quickly recovers following deformation - i.e. regain strength rapidly, in hours rather than days (Wotherspoon & Ashley, 1992).
- Measured yield strengths generally exceed by several orders of magnitude the likely applied shear stresses from sewage flowing over the deposits (Ashley et al., 1992 and Wotherspoon, 1994).
- Yield strengths vary with solid/liquid phase proportions and bulk density - hence any depth layering or consolidation effects are important (Ashley et al., 1992 and Wotherspoon, 1994).
- A relationship for bed yield stress τ_y, related to bed moisture content m (%) has been developed for fine (d_{50} < 1.0mm) cohesive-*like* deposits, which may be used to predict the onset of erosion (Wotherspoon, 1994), the relationship obtained is illustrated in equation 6;

$$\tau_y = 0.966 \times 10^8 \, m^{-3.1682} \; \left(\mathrm{N/m^2}\right) \qquad ....6$$

Despite the work undertaken investigating the yield point of sewer sediments, little is known of the strength of the crust of the sediment deposit (Crabtree & Clifforde, 1990).

2.4 Sediment Transport

The physical processes involved in the movement of sediment particles through a sewer system are, essentially, the same as those employed in open channel hydraulics. There are five important differences which principally relate to boundary conditions;

1. Sewers have a rigid boundary.
2. There is a limited amount of material available for erosion into the flow.
3. Inputs vary considerably on a micro and macro scale.
4. Sewers may, on occasion, operate in a surcharged condition.

5. Due to the boundary conditions in sewers, bed shear distributions have been found to vary markedly (Kleijwegt, 1992).
6. Where bed forms exist the proportionate energy losses associated are considerably more than that experienced in rivers (Kleijwegt, 1992).

Where flows are over a deposited bed the particles in the deposit will be subject to lift and drag forces. If these forces exceed the restoring forces on the particles the particle will be eroded in to the flow. In sewer sediments the restoring forces are principally; the self weight of the particle, interlocking forces with the surrounding material and possibly any cohesive-*like* characteristics the material exhibits. The erosion procedure is further complicated by the continuously varying turbulent nature of the flow at the bed.

Once a sediment particle has been entrained into the flow it will travel through the system in one, or both, of two modes of transport;

1. Suspension - it is principally small and light particles which are transported in this mode of transport during DWF conditions, however during storm conditions the characteristics of the material moving in this transport mode will change.
2. As 'bed-load' - this consists of particles moving near the bed, which whilst in transport, maintain some contact with the bed, by rolling or saltating, as demonstrated by Francis (1973). Larger solids, grits and gravels, may take several months to move relatively short distances as bed-load, whilst lighter (faecal) solids may travel through the entire system in a matter of hours.

There is no distinct separation between transport in suspension or as 'bed-load' other than arbitrary descriptive definitions, although it is accepted that transport in suspension becomes significant when the terms indicated in equation 7 are met (Raudkivi, 1990, Ashley et al., 1993a, Butler et al., 1995a and Ashley and Verbanck, 1996). Additionally some researchers classify transitory modes of transport (saltaion) to aid analysis (Ashley and Verbanck, 1996 and Wotherspoon, 1994).

$$\frac{u_*}{w_s} \rangle 0.75 \qquad \text{....7}$$

2.4.1 Initiation of Motion

The point at which a particle is eroded from the bed and entrained into the flow is termed the *initiation of motion*, or *incipient motion*. It is the amount by which the criterion, which defines the initiation of motion, is exceeded that controls the transport capacity of the flow for the given particle characteristics under consideration (Du Boys, 1879).

Due to the continuously varying nature of the flow at the boundary with the sediment bed it is difficult to define the exact point of the initiation of motion, however there are two possible methods of definition (Graf, 1984, Lavelle & Mofjeld, 1987 and Raudkivi, 1990). The first is based on a minimum transport rate criterion as proposed by Kramer (1935), Shields (1936), and Lavelle & Mofjeld (1987).

The work undertaken by Shields is recognised as being seminal in this field (Vanoni, 1984, Ab. Ghani, 1993, Graf, 1984, Kleijwegt et al., 1990 and Raudkivi, 1990). Shields defined the threshold of movement as a *zero transport rate* based on the extrapolation of experimental plots. The plots concerned take the form of a dimensionless entrainment parameter (τ_*) plotted against the shear Reynolds number (R_*), which are defined in equations 8 and 9 respectively.

$$\tau_* = \frac{\tau_c}{\rho g(s-1)d} \qquad ....8$$

$$R_* = \frac{du_{*,cr}}{\nu} \qquad ....9$$

The original plot by Shields (1936), Shields diagram, was based on work considering the transport of granular spherical solids positioned on a flat bed. To widen the applicability of the work of Shields, the scope of the diagram was later extended by Rouse (1937) and Mantz (1977), and it is the modified form which is illustrated in Figure 6.

In a later evaluation of bed-load transport van Rijn (1982a) updated the Shields diagram by expressing τ_* in terms of a critical mobility number, θ_{cr}, and this is plotted against the particle number D_*. θ_{cr} and D_* are defined in equations 10 and 11 respectively, the relationship between the two parameters is illustrated in Table 5 and Figure 7.

$$\theta_{cr} = \frac{\left(u_{*,cr}\right)^2}{(s-1)gd_{50}} \qquad ....10$$

$$D_* = d_{50}\left(\frac{(s-1)g}{\nu^2}\right) \qquad ....11$$

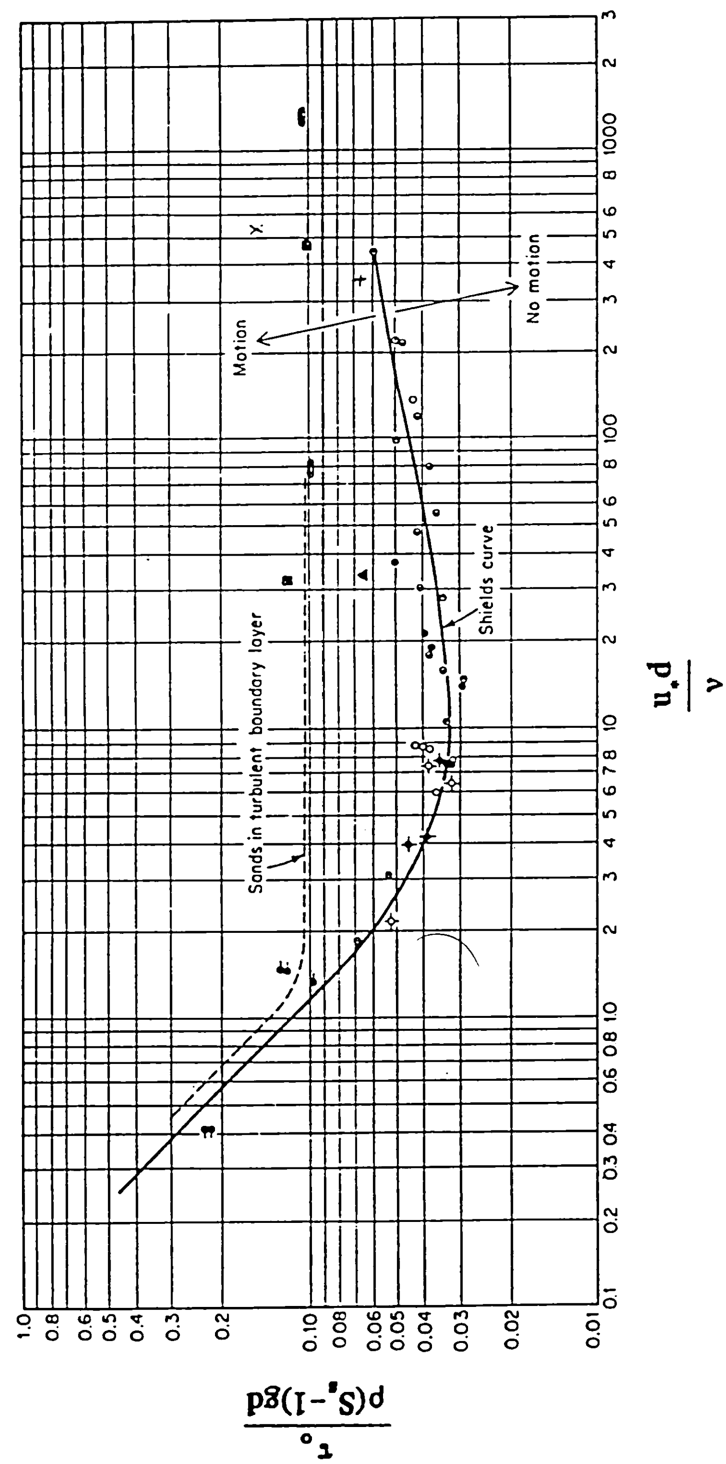

Figure 6 : Shields Diagram (from Graf and Acaroglu, 1968)

TABLE 5 : θ_{cr} VARIATION WITH D*, AFTER VAN RIJN (1982a)

D* Range	θ_{cr}
$D_* \leq 4$	$\theta_{cr} = 0.24 D_*^{-1}$
$4 \leq D_* \leq 10$	$\theta_{cr} = 0.14 D_*^{-0.64}$
$10 \leq D_* \leq 20$	$\theta_{cr} = 0.04 D_*^{-0.10}$
$20 \leq D_* \leq 150$	$\theta_{cr} = 0.013 D_*^{0.29}$
$150 \leq D_*$	$\theta_{cr} = 0.055$

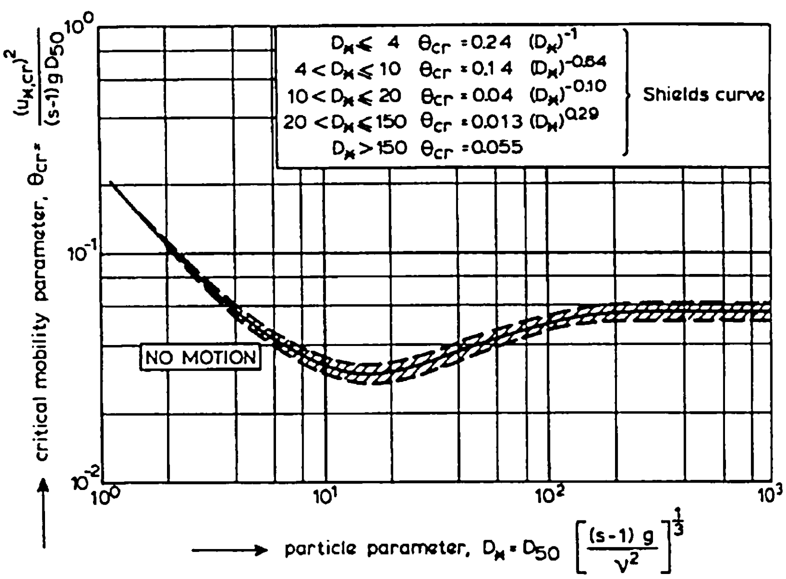

Figure 7 : θ_{cr} versus D*, after van Rijn (1982a)

The second definition of the initiation of motion is based on observations made as part of laboratory studies undertaken investigating incipient motion in rigid boundary channels (Novak & Nalluri, 1975, 1978 & 1984, Ojo, 1978 & 1980 and El-Zeamey, 1991). Based on work in 152mm and 305mm internal diameter circular channels and a rectangular channel 305mm wide, Novak and Nalluri (1975 & 1978) investigated the incipient motion of individual cohesionless particles (sands and gravels) over a wide range of particle sizes (0.6mm - 50mm) and, based on the theoretical analysis of the results, equations 12 and 13 were obtained, for rectangular and circular channels respectively.

$$V_t = 0.17(s-1)^{1/2} d^{0.24} \qquad ....12$$

$$V_t = 0.16(s-1)^{1/2} d^{0.16} \qquad ....13$$

The work of Novak and Nalluri (1975 & 1978) failed to take into account the affect of bed roughness and interlocking of a given particle with the surrounding sediment bed, and to overcome this apparent problem Ojo (1978 & 1980) investigated the effect of particle grouping, particle spacing and channel roughness. Novak and

Nalluri (1984) augmented the studies undertaken by Ojo (1978 & 1980) with their earlier work and re-analysed the results and obtained equation 14.

$$\frac{V_t}{\sqrt{gd}} = 0.5(s-1)^{1/2}\left(\frac{d}{R}\right)^{-0.40} \qquad ....14$$

Although the work of researchers investigating the initiation of motion of cohesionless sands and gravels in laboratory studies is considerable, there is still a significant amount of knowledge to be gained if the incipient motion in real sewers is to be understood. This is mainly due to the cohesive-*like* properties of combined sewer sediment along with significantly lower particle specific gravities - U.K. average 1.72, (Crabtree, 1989).

2.4.2 Suspension

The suspended mode of sediment transport is by far the most important mode, in terms of mass transported, and recent field studies have shown that it accounts for at least 88% of the total mass of material transported (Coghlan, 1995 and Butler et al., 1995a). Suspended solids variations in the sewer system are typically well correlated with liquid inputs to the system (Crabtree et al., 1993), during DWF conditions.

2.4.2.1 Initiation of Suspended Sediment Transport

Once a sediment particle has been entrained into the flow, via either erosion from a deposited bed, or direct entry to the system, it may be transported in the suspended mode of transport. Bagnold (1966) defines suspended particle transport as;

> **"...when the turbulent eddies have dominant vertical components which exceed the particle's fall velocity..."**

and proposed equation 15, based on the work of Schmidt (1925) and O'Brien (1933) to define the initiation of the point at which particle transport is considered as suspension;

$$\tilde{w} = \left[(w')^2\right]^{1/2} \geq w_s \qquad ...15$$

Where : w' = Vertical flow velocity fluctuation

w_s = Particle settling velocity

$\tilde{w}$ = Vertical turbulence intensity

Based on a later study, Hinze (1975) observed that the maximum value of vertical turbulence, $\tilde{w}$, was of the same order of magnitude as the bed shear velocity, u_*, and the parameters were correlated. Using these findings equation 16 was obtained.

$$\frac{u_{*,cr}}{w_s} \geq 1 \qquad ...16$$

Where $u_{*,cr}$ is the critical bed shear velocity at the initiation of suspension.

In an earlier, and less substantial study, Engelund and Hansen (1967) obtained equation 17, which may be used to define the point at which a sediment particle may move into suspension.

$$\frac{u_{*,cr}}{w_s} \geq 0.25 \qquad \text{...17}$$

With the aim of assessing the results of earlier work, a study at the Delft Hydraulics Laboratory (D.H.L., 1982) van Rijn, 1982b added to the work undertaken in this field. The main result of this study was that it included more details in the definition in relation to particle characteristics, as illustrated in equations 18 and 19. The particle parameter, D_*, is defined in equation 20.

$$\frac{u_{*,cr}}{w_s} = \frac{4}{D_*}, \quad \text{for } 1 \langle D_* \leq 10 \qquad \text{...18}$$

$$\frac{u_{*,cr}}{w_s} \geq 0.25 \qquad \text{...19}$$

$$D_* = d_{50}\left[\frac{(s-1)g}{v^2}\right]^{1/3} \qquad \text{...20}$$

Although there are large discrepancies in the definition of the initiation of sediment transport in suspension (Lavelle & Mofjield, 1987) recent literature (Raudkivi, 1990, Ashley et al., 1993a, Butler et al., 1995a and Ashley and Verbanck, 1996) have adopted the relationship illustrated in equation 21 as the point at which suspended sediment transport becomes significant.

$$\frac{u_{*,cr}}{w_s} = 0.75 \qquad \text{...21}$$

This relationship is pertinent as it is idealised as representing the turbulent flow conditions present at the bed (Mehta & Partheniades, 1975). However, it is often overlooked that entrainment will not take place where the transport capacity of the flow has been reached in the region of the flow concerned (Shen, 1981 and Arora et al., 1984).

2.4.2.2 Suspended Solids Transport Relationships

There are a large number of laboratory based solids transport models available for the prediction of solids transport, notably;

<u>Transport at limit of deposition</u>	<u>Incipient motion studies</u>
Ambrose (1953)	Kalinske (1947)
Durand and Condolios (1956)	Ippen (1971)
Laursen (1958)	Macke (1983)

Graf and Acoraglu (1968)
Robinson and Graf (1972)
Mantz (1977)
Nalluri and Mayerelle (1989)

Transport over a deposited bed
Rouse (1950)
van Rijn (1984)

Alvarez (1990)

Total load over a deposited bed
Bagnold (1966)
Engelund and Hansen (1967)
Sonnen and Field (1977)
Ackers & White (1973) and
Ackers (1984 &1993)

Although there has been a considerable amount of work undertaken investigating suspended solids transport, much of it is difficult to apply to solids transport in sewers. This is principally due to three factors (Clemens, 1988, Kleijwegt 1992a, 1993, Ackers et al., 1994, Coghlan, 1995 and Butler et al., 1995b):

1. The majority of the models were not developed for application to sediment transport in sewers, but for other situations (i.e. estuarine studies, pipe flow, open channel flow, etc.).
2. The sediment concentrations considered are, generally, much higher than those observed in sewers, up to ~10000 ppm compared with the maximum observed in sewers which, typically, does not exceed 1000mg/l (~1500ppm, assuming a suspended sediment specific gravity of 1.5) even in storm events.
3. Many of the parameters used in the development of the models may be difficult to measure in the field, even as part of a dedicated fieldwork programme.

CIRIA (Ackers et al., 1994 and Butler et al., 1995) recognise that many of the models may not be applicable to suspended sediment transport in sewers, and in an evaluation recommend the use of the models obtained by Macke (1983) and the Ackers-White model (Ackers & White, 1973 and Ackers, 1984 & 1983) for transport with and without a deposited bed respectively. The Macke (1982 & 1983) and Ackers-White relationships are illustrated in equations 22 and 23, the development of these relationships is discussed in Chapter 4.

$$C_v = \frac{\lambda_c^3 V_L^5}{30.4(s-1)w_s^{1.5}A} \qquad \ldots 22$$

$$\frac{u_{*,cr}}{w_s} \geq 0.25 \qquad \ldots 23$$

In Dundee, Coghlan (Coghlan et al., 1995 & Coghlan, 1995) undertook an evaluation of existing suspended sediment transport models, as well as developing a new methodology, this is discussed in section 3.2.1.

2.4.2.3 Suspended Solids Variation with Depth

The mass of material transported in the zone of the flow column where movement as suspended load predominates may be idealised as being made up of two distinct fractions. The first being fine particles, predominately less than 40 μm in diameter and of high organic content (Verbanck, 1990 and 1992), which are uniformly distributed throughout the flow column. The second fraction is made up of larger sediment particles which are observed to be transported as a heterogeneous mix (Urcikán, 1984) within the flow column The relative sediment concentration at each point being primarily dependent on the velocity distribution in the flow (Vanoni, 1984).

The definitive work in this field was undertaken by Rouse (1937) using, as basis, the work of von Karman (1934) in establishing a logarithmic solids and velocity profile, the von Karman relationship is shown in equation 24.

$$\ln\frac{c}{c_a} = -\rho w_s \int_a^y \frac{du}{dy}\frac{dy}{\tau} \qquad \text{...24}$$

Where : c = Sediment concentration at level y

c_a = Sediment concentration at level a

w_s = Particle settling velocity

τ = Shear Stress at level y

Rouse (1937) integrated this relationship, to obtain that illustrated in equation 25.

$$\frac{c}{c_a} = \left[\frac{d-y}{y} \times \frac{a}{d-a}\right]^{w/\kappa u_*} \qquad \text{...25}$$

Where κ is the von Karman constant, 0.4 for clear water.

The form of relationship indicates that it will give unrealistic sediment concentrations at the two extremes, i.e. zero at the free surface and infinity at the bed/invert. Although the relationship obtained by Rouse (1937) is accepted, several attempts have been made to update it, usually by altering the log velocity distribution. Ippen (1971), used the distribution obtained by Krey (1927), and it has been shown (Daily & Chu, 1961, Daily & Hardison, 1964 and Elata & Ippen 1961) that the 'constant', κ, does not remain constant when the particulates concerned have a specific gravity approaching unity. Additionally, Vanoni (1953) and Einstein and Chien (1952 & 1955), in an evaluation of the relationship, observed that at high sediment concentrations, not typical of those experienced in sewers, the accuracy of the relationship decreased. Additionally the Rouse relationship only presents a two dimensional particle concentration distribution, with only a limited amount of work being undertaken investigating three dimensional distributions, principally Vanoni (1944). However, the Rouse relationship remains the definitive relationship for prediction of the sediment concentration profile in flows, and has been used with some success in recent years in field (Ristenpart et al., 1995) and laboratory (Skipworth, 1995) sewer studies, as well as in simulated estuarine conditions (Ali & O'Connor, 1995).

Verbanck (1995) made detailed observations relating to a supposed suspended solids variation with depth in the Brussels sewer systems, this work is discussed in more detail in section 3.2.

2.4.3 Bed-Load

This section will deal, principally, with the observations made in the field by researchers relating to the material moving at the bed in sewers. Additionally, the classical bed-load work in alluvial studies will also be described. It will not, however, deal with the considerable amount of laboratory based research undertaken investigating transport at the bed in laboratory flumes, this work is dealt with in detail in Chapter 4.

Solids in combined sewers are markedly different to those transported in natural watercourses. Of particular importance are the large organic solids which originate, principally, from domestic sanitary inputs. It is accepted that some of this material, together with organic material from surface inputs, degrades to form the organic fraction of the suspended loads and bed deposits in sewers (Jefferies & Ashley, 1994 and Bertrand-Krajewski et al., 1995). These large organic fractions are comprised of faeces, textiles, paper, food stuff and surface derived solids (vegetation etc.), and are present at all depths in the flow column due to their low specific gravity ($\cong$1). In some sewer systems, high concentrations of this material are found moving near the bed of the sewer (McGregor & Ashley, 1990, Ashley et al., 1992, and Ashley et al., 1993 & 1994, Lin et al, 1993a & b, Coghlan, 1995, and Verbanck, 1995).

The relative significance of solids moving at the bed in sewers, and their associated pollutants, relate to both hydraulic and polluting effects:

- Inorganic bed-loads are the primary vector of solid deposits in sewers (Lin et al, 1993a & 1993b, Lin & Le Guennec, 1995 Bertrand-Krajewski et al., 1995).
- The material moving at the bed in sewers conveys a disproportionate pollution load, via very high concentrations. These may settle to (and enter) the bed, be conveyed through sewer networks to treatment plants or be discharged into the environment via CSOs, depending upon changing hydraulic conditions (Verbanck, 1995).

There is a degree of uncertainty concerning the interface between the solids conveyed in true suspension and those which comprise the bed, as evidence suggests an intermediate 'layer' of material at the base of the water column which may or may not be in motion, depending upon the hydraulic conditions (Geiger, 1984 &1987). Observations using small diameter tubes extracting samples from the flow and near the bed by Ashley et al. (1994), Verbanck (1995), Wöhrle & Brombach (1991) and Ristenpart et al. (1995), indicate that there may be a lower zone of highly concentrated material close to the bed which may or may not be in motion, depending upon the hydraulic conditions. There are major differences both spatially, even within the same sewer, and also temporally in response to changing inputs (particularly storm flows) and any other cause of unsteady flows. It is clear that there are important variations in observations related to the matter in transport near the bed which may be summarised as given in this section.

2.4.3.1 Traditional Concepts

There are two principal, descriptive, definitions of what constitutes bed-load transport in pipes and channels, these are proposed by Bagnold (1973);

> **"...that in which the successive contacts of the particles with the bed are strictly limited by the effect of gravity..."**

and by Einstein (1944) as;

> **"...the transport of sediment particles in a thin layer of 2 particle diameters thick just above the bed by sliding, rolling and sometimes making jumps of a few particle diameters..."**

Although the definition of Einstein (1944) gives a concise definition of bed-load and its boundary with the suspended mode of transport, it is somewhat difficult to use in the field studies. Raudkivi (1990) defines transport as bed-load and saltation using the definitions illustrated in equations 26 and 27 respectively.

$$\text{Bed}-\text{Load} \quad 6 \rangle \frac{w_s}{u_*} \rangle 2 \qquad ....26$$

$$\text{Saltaion} \quad 2 \rangle \frac{w_s}{u_*} \rangle 0.6 \qquad ....27$$

Traditional bed-load theory is based on the work of Du Boys (1879) who proposed a method for the prediction of the rate of sediment transport as bed-load in streams. The form of the relationship is illustrated in equation 28.

$$g_s = \Psi\tau_o(\tau_o - \tau_c) \qquad \text{....28}$$

Where g_s is the transport rate per unit width per unit time, and Ψ is a coefficient dependent on sediment size, as defined by Straub (1935). The work of Du Boys (1879) has been the basis for several subsequent relationships which have used the critical shear stress criterion for initiation of motion, notably Shields (1936), Meyer-Peter & Muller (1948), Yalin (1963) and Bagnold (1966).

The next main advance in the field of bed-load transport was based on the work of Schoklitsch, reported by Shulits (1935), where the effect of invert slope and particle characteristics were given greater importance. The relationship is cumbersome to apply however, as the transport rate for each size fraction must be calculated separately and then the sum calculated. The relationship obtained is illustrated in equation 29 (imperial units).

$$g_s = \frac{86.7}{\sqrt{d''}} s^{1.5}(q - q_c) \qquad \text{....29}$$

The work which has had the greatest importance to sediment transport engineers is perhaps that of Shields (1936) who expressed the critical shear stress term defined by Du Boys (1879) in terms of a dimensionless critical shear stress parameter, τ_*, (equation 30) and related it to the bed Reynolds number, R_* (equation 31).

$$\tau_* = \frac{\tau_c}{\rho(s-1)d} \qquad \text{....30}$$

$$R_* = \frac{u_* d}{\nu} \qquad \text{....31}$$

Using these relationships, via the Shields diagram (as described in section "2.4.1 Initiation of Motion"), it became possible, in theory, to determine the point at which a specific particle would be entrained into the flow.

Based on a physical approach, and avoiding the use of a shear threshold parameter, Einstein (1942 and 1950) and Brown (1950) made the next big step in sediment transport which has been the basis for several subsequent transport models (e.g. Shen and Hung, 1983, Perrusquía and Nalluri, 1995 and Torfs, 1995). The relationship obtained by Einstein is shown in equation 32

$$\Phi_b = 40\Theta_g^{3.0} \qquad \text{....32}$$

Where Φ_b, the transport parameter, and Θ_g, the mobility parameter, are illustrated in equations 33 and 34.

$$\Phi_b = \sqrt{\frac{q_b}{g(s-1)d_{50}^{3.0}}} \qquad \text{....33}$$

$$\Theta_g = \frac{u_*^2}{g(s-1)d_{50}} \qquad \text{....34}$$

Although the definition of Θ_g changes where the affect of bed-forms become significant (Engelund and Fredsøe, 1982).

Chein (1954), later updated the work of Einstein to obtain the relationship illustrated in equation 35.

$$\Phi_b = \left(0.25\Theta_g - 0.188\right)^{1.5} \qquad \text{....35}$$

Meyer-Peter and Muller (1948) obtained a relationship which is still widely used today in its original form, which is illustrated in equation 36, where g'_S is the buoyant weight transported per unit time per unit width and is defined in equation 37.

$$0.25\sqrt[3]{\rho_w}\,\frac{g_s'^{2.5}}{d} = \frac{\gamma R_h \left(\frac{k}{k'}\right)^{1.5} S}{d} - 0.047\rho_w(s-1) \qquad \text{....36}$$

$$g'_s = \rho g_s \frac{(s-1)}{s} \qquad \text{....37}$$

Although much of the early work investigating sediment transport as bed-load in streams and channels may seem unimportant when assessing transport at the bed in sewers, it does, however, have 3 relevant aspects

1. Much of the work has a sound physical basis.
2. The relationships, largely, rely on parameters which are readily determined.
3. The relationships themselves have been the starting point for many recent advances in this field (Vanoni, 1984).

2.4.3.2 Field Based Observations

To date, only a limited amount of work has been undertaken in field based studies investigating transport at the bed in sewers (Clark, et al., 1993) much of which is only suppositional or relies on precarious data collection protocols.

The studies by Lin et al. (1993 a & b) in Marseille using traditional 'bed-load' traps attempted to look at material moving in this mode. Tests were carried out in Marseille (Lin et al., 1993a and 1993b), utilising two bed-load traps, one downstream of a steep sewer section, gradient 1.78% and the other located in a section where the gradient was only 0.1%. In the former trap, the particles were virtually exclusively inorganic, typical size 2-3mm (up to 10mm), whereas in the second trap, the particles had characteristics (other than particle size distribution) similar to those observed in suspension and had specific gravity variations from that obtained upstream down to around 1.5 .

The evolution of the bed deposits including both erosion and deposition in the Marseille No.13 trunk sewer was shown to be predictable over a period of 1000 days with a 'bed-load' relationship derived (Lin & Le Guennec, 1995) from the Meyer-Peter (Meyer-Peter & Muller, 1948) equation, taking into account a mixing layer and grain size classes, d_i, the relationship is illustrated in equation 38;

$$\frac{q^*_{s,i}}{\sqrt{(s-1)gd_i^3}} = 8\left(\tau_i^* - \tau_{c,i}^*\right)^{3/2} \qquad \text{....38}$$

Where $q*_{s,i}$ is the unit-width bed-load transport rate capacity under equilibrium conditions, d_i the grain size (in each group), τ_i* and $\tau*_{c,i}$ the non-dimensional bed and critical shear stresses respectively. Temporal changes to transport rates at any section were determined using the relationship developed by Daubert & Lebreton (1967), which gives the rate of change of the local solids discharge, $q_{s,k}$, as a function of the particle fraction settling velocity, the shear velocity and a coefficient α, where this corresponds to erosion when $q*_{s,i} > q_{s,i}$ and conversely to deposition. For both erosion and deposition, α was recommended as 0.01. The methodology outlined by Lin & Le Guennec (1995) for the prediction of long term solids deposition highlights the emphasis the researchers place on the near bed solids in transport as a source of material for deposition.

The inorganic granular material moving at the bed in sewers, which may be viewed as a true 'bed-load' will very rarely travel in true suspension during DWF (Butler et al., 1995a & b and Ashley and Verbanck, 1996). It is of major importance, because it is found throughout sewerage systems and when arrested, is responsible for the build up of the bulk deposits within sewers. Recent initiatives to control sediments in sewers have begun to appraise the effectiveness of traditional grit traps for the protection of downstream sewer lengths (Bertrand-Krajewski et al., 1995), other methods are, however less conventional (Lorenzen & Ristenpart, 1995 and Chebbo, et al., 1995).

Verbanck (1995) identified a highly concentrated transport zone above the bed in a large sewer in Brussels (gradient 0.025%), based on a solitary sample. Similar zones were observed in Hildesheim by Ristenpart et al. (1995) and elsewhere in Germany by Wöhrle and Brombach (1991). Concentrations of solids were measured up to more than 3500mg/l, compared with typical DWF suspension concentrations of 200-500mg/l. This very fluid, dense, liquid-solid mixture may exhibit the characteristics of a Bingham fluid and the solids contained therein may be highly organic. The concentrations reported in Belgium and German studies are open question, this is principally due to the method of sampling, i.e. a via small diameter hose positioned just above a sediment bed which is known to contain a significant proportion of fine particles, which may also be sampled.

Due to the apparent differences in the material moving at the bed at different study sites a number of terms have evolved to describe it;

- fluid mud (Simons and Senturik, 1992)
- fluid sediment (Ristenpart et al., 1995)
- dense undercurrents (Verbanck, 1995)
- organic near-bed fluid
- near-bed solids (Ashley et al., 1995)

The concept of considering the material in transport at the bed as a fluid is consistent with early estuarine studies (Kalinske, 1947). Initially the term 'fluid sediment' was used because of the similarities between this material and 'fluid muds' found in estuarine studies (Ali et al., 1992 and West, 1992). Fluid muds develop as a result of high suspended sediment concentrations. In estuarine conditions a gradual increase in suspended sediment concentration in the fluid column towards the bed can reach a point where there is a rapid increase in concentration with zero or very little increase in depth. This increase can be to the mud layer which may comprise a mobile part overlying a stationary mud. Typical fluid mud densities are 1030-1250 kg/m^3. At the base of the stationary mud may be another sharp increase in concentration (bulk density) to the gel point which marks the boundary of an unconsolidated 'structure' and a consolidating bed which has developed some effective yield strength. A possible application of these concepts to sediments in sewers is illustrated in Figures 8 & 9. However there is no direct evidence that sediment is transported as a *dense undercurrent* or *fluid mud* in any sewer system.

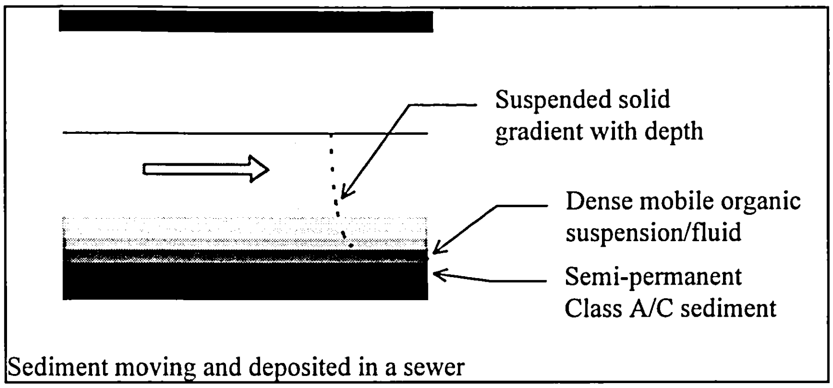

Figure 8 : Simplistic model of near-bed solids in sewer systems
(adapted from Ashley and Verbanck, 1996, Torfs, 1995 and Ali et al, 1992)

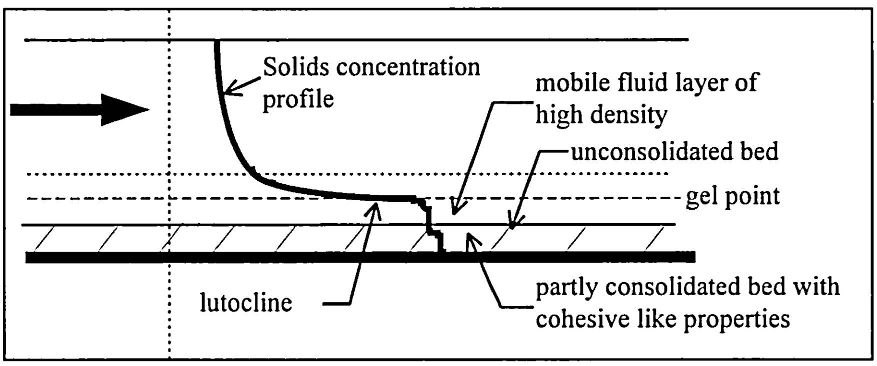

Figure 9 : Possible model of near-bed solids in sewer systems
(adapted from Ashley and Verbanck, 1996, Torfs, 1995 and Ali et al, 1992)

Additionally, as muds are homogeneous, it is not clear whether these concepts are applicable to sewer sediments, as they comprise a variety of particle sizes and types and may be laid down in mixtures or stratified, in which case the density variation with depth will be more complex. For the time being, the terms 'dense undercurrents' and more recently, simply 'near bed solids' (Ashley et al, 1995 and Ashley & Verbanck, 1996) are currently in vogue. It is possible that there are perhaps different types of near bed layers in sewers, some of which may in fact occur concurrently, this may justify, to some extent, the debate concerning an accurate descriptive term for the material moving at the bed in sewers. The term Near Bed Solids (NBS) is used in this study as it is seen as an accurately describing sediment transport near the bed in <u>every</u> sewer where this material is in transport regardless of the material characteristics. Additionally, much of the alternative terms imply a distinct physical separation between the material transport as bed-load and that in moving in suspension, which is not the case. Although this clear distinction may be an advantageous simplification when modelling the material in transport as near bed solids, it does not enhance the understanding of the phenomena.

Verbanck, (1995) considered that for the *dense undercurrent* there is an 'inner suspension' region, which will (over a depth of 150mm in the Brussels sewer) have marked changes in the particle size characteristics and relative concentration and can contain relatively large (0.5mm, organic content >90%) particles in a 'trapped' matrix of 'suspended' flow, with particles not actually in contact with the bed. The particles in this region are notably different from those found in the flow which are finer. Under low flows the layer may become stationary and appear to deposit on top of the coarser bed as a weak surfacial layer (Class C sediment). Supposition evidence indicates that when there is a flow, the material may remain in a zone of fluid just above the bed in which the particles are trapped in a 'hindered settlement' matrix, never being able to actually reach the underlying bed, and supported by the strong turbulent diffusion in this zone of steep velocity gradient. Whether the material deposits on the bed or not, and because of its very weak shear resistance, the material may be considered to be constantly available *in limine* (on the threshold) as it will erode, at least in part, as soon as bed shear stresses begin to increase (Verbanck et al, 1992 and Ashley and Verbanck, 1996).

The potential erodibility of this material and associated pollutant release has been examined by carrying out a series of controlled laboratory tests on samples of these sediments, as described in McGregor et al, (1993). These considered the potential for pollutants remaining in suspension once eroded, in solution or attached to fine or coarse sediment fractions, and the potential for subsequent deposition. The test revealed that of the total 100% available, some 52% of the COD, 53% of BOD, 56% of the total solids, 53% of the volatile solids and 71% of the ammonia were 'released' by the erosion of the near-bed layer. The major proportions of each of these released pollutants were either associated with the finest particles or were in the dissolved phase and were hence unlikely subsequently to re-deposit within the sewer.

2.5 Bed-Forms

In some sewers the upper layers of sediment deposits can be considered as a very slow moving mass named bed-forms. Bed-forms can be divided into the following three categories, based on their physical characteristics (Engelund & Hansen, 1967 and Kleijwegt, 1992a & b, and 1993):

1. Continuous flat mobile beds - this type of bed will occur when there is little or no motion of particles or when there is high shear stress.
2. Discontinuous beds with isolated forms - these being either *dunes* or *ripples*. Dunes can be defined as regular bed-forms with straight crests perpendicular to the flow direction, with a length greater than the depth of

flow. Ripples are more irregular, and their length will not exceed the flow depth.

3. Discontinuous beds with isolated forms - this formation will occur when the troughs of the dunes/ripples reach the invert of the sewer. These formations are believed to result in significant head losses (May, 1977, Mark, 1992 and May, 1994).

A considerable amount of work has been carried out investigating bed-forms in alluvial channels (Meyer- Peter & Müller, 1948, Pratt, 1973, Yalin 1964, Fredsøe, 1979 and van Rijn 1984), however, the investigation of bed formations in sewers is limited (e.g. May, 1977, Perrusquía, 1988, Kleijwegt, 1992)and May, 1994, these studies being largely laboratory simulation based.

Continuous beds can be classified by two methods (Kleijwegt, 1992), both of which assume the material concerned is non-cohesive:

1. Froude number (F_r) in excess of 0.5 as proposed by Garde and Ranga-Raju. (1985)
2. The application of a method developed by van Rijn (1984) which entails the graphical interpretation of data.

Kleijwegt (1992) suggests that the classification of discontinuous beds is largely dependent on the supply of sediment, although the velocity distribution near the bed may also be important (Samaga et al., 1986a, b & c), as bed-forms are only discontinuous where a continuous bed has been partially eroded and not subsequently replaced.

Several researchers have proposed methods for predicting the bed-form dimensions in alluvial channels (Fredsøe, 1982, van Rijn 1984 and Yalin 1977). In his study, Perrusquía (1988) compared each of these methods with his laboratory observations. It was found that where ripples were considered the method proposed by Yalin gave the closest approximation to what was observed. However, where dunes were considered, van Rijn's method was the most accurate, giving a estimate of -50% - +100% of the actual value.

2.6 First Flush

In many, but not all, sewer systems a distinct peak in pollutant concentrations is observed just before the peak in the storm flow hydrograph, This phenomenon is termed first flush. The pollutants in the first foul flush are thought to originate from two main sources; erosion of any sediment bed present, and from entrainment of the highly organic material moving at the bed in some sewers (Crabtree et al., 1994).

As runoff enters a sewer the increase in flow can cause either dilution or flushing (Geiger, 1987 and Saget et al., 1995). Dilution is the process whereby the concentration of pollutants in the sewer are reduced by the ingress of runoff water, and is common when there is a lack of pollutant supply (i.e. bed sediment), or where the rainfall event is of low intensity. Flushing is caused when there is a sufficient supply of pollutants which can be eroded and entrained into the flow. This flushing effect is termed, in general, *first flush*. Stotz and Krauth (1984) define first flush as when

> **"...the maximum pollution load in kg/min appears before the maximum water flow in m^3/min and the pollution load decreases at a more rapid rate than the water flow."**

Stotz and Krauth (1984) hypothesised that the variation in pollutant load in a time step, $f_i(t)$, results from the independent variation of flowrate q(t) and pollutant concentration, $c_i(t)$. By integrating $f_i(t)$ over the runoff duration of a storm event loading curve, $F_i(t)$ can be obtained using equation 39;

$$F_i(t) = \int_0^t q(t).c_i(t)dt \qquad ....39$$

To demonstrate the magnitude of the flushing, or compare the flushing effects of different storms or catchments it is possible to plot the cumulative load against the cumulative flow for the duration of the storm. If the plot is linear no change has occurred and the situation is defined as the equilibrium condition (Geiger, 1987), i.e. the pollution concentration has not changed. Any deviation from the equilibrium condition indicates dilution or flushing. If the relationship is above the equilibrium condition, flushing has occurred, if it is below the flow has been diluted. This is illustrated schematically in Figure 10.

The description of first flush proposed by Stotz and Krauth (1984) differs from that offered by Pearson et al., (1986), who define the process as

> **"...the initial period of a storm flow during which the concentration of pollutants is significantly higher than those observed during the latter stages of the storm event."**

Based on extensive data collected in Great Harwood, Pearson et al. (1986) were able to categorise flushes into two distinct groups;

1. Type A.
2. Type B.

Type A first flushes are characterised by suspended solids (SS) and chemical oxygen demand (COD) concentrations that are less than the ambient DWF conditions(i.e.

dilution). It was found that in such an event the SS and COD flush would last no longer than 30 minutes, after which their concentrations would rise rapidly.

First flushes defined as Type B were found to have a pollutant concentration in excess of those observed in DWF conditions. Researchers found that this type of flush tended to occur after an antecedent dry weather period (ADWP) of at least three days and generally lasted 30-45 minutes. The occurrence of each type being linked to the ADWP by Thornton and Saul, (1986).

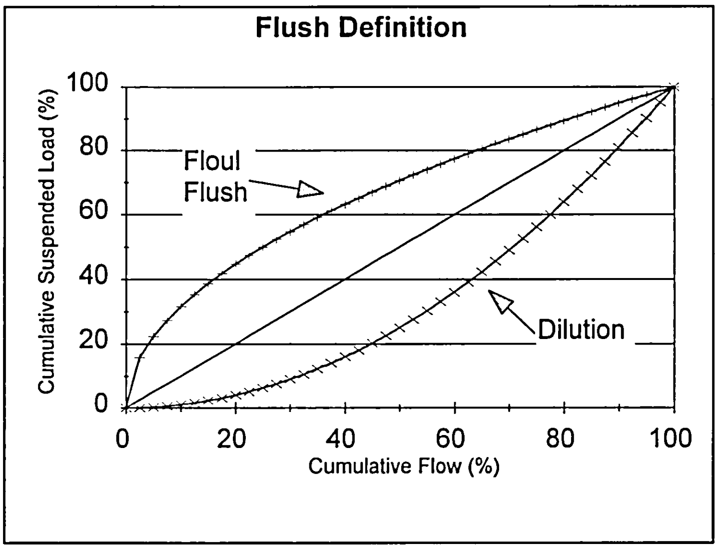

Figure 10 : First flush definition used by Stotz and Krauth (1984)

Saget et al., (1995) propose a third definition of what constitutes first flush;

> **...when at least 80% of the pollution load is transferred in the first 30% of the (flow) volume...**

and defined the shape of the curve in a similar form to that proposed by Geiger (1987) using equation 40.

$$Y = X^a \qquad \text{....40}$$

Where Y and X are the proportion of the total pollutants transported and the proportion of the total flow passed a given point at a given time after the start of the storm, and 'a' is an event specific parameter which defines the shape of the curve. Ranges for 'a' are given Table 6 and illustrated graphically in Figure 11.

TABLE 6 : DEFINITION OF 'a' (Saget et al., 1995)

AREA	'a' Range	Definition of Event
1	$a \leq 0.185$	Strong deviation above diagonal
2	$0.185 < a \leq 0.862$	Moderate deviation above diagonal
3	$0.862 < a \leq 1.000$	Little deviation above diagonal
4	$1.000 < a \leq 1.159$	Little deviation below diagonal
5	$1.159 < a \leq 5.395$	Moderate deviation below diagonal
6	$5.395 < a$	Strong deviation below diagonal

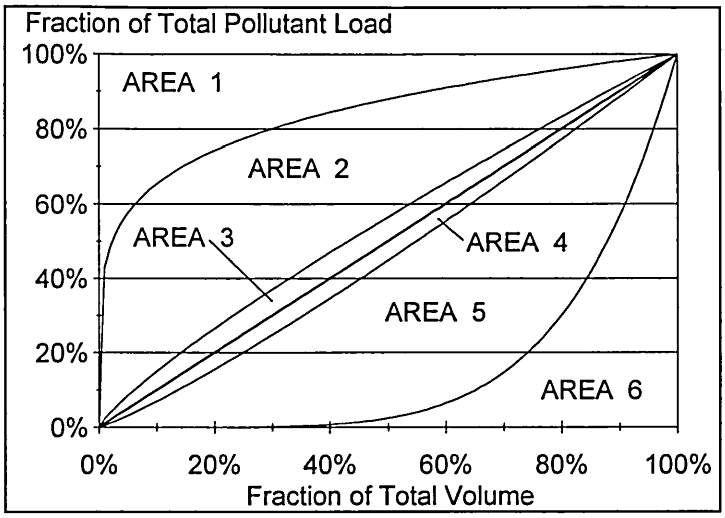

Figure 11 : Definition of 'a' (Saget et al., 1995)

Based on the definition of Saget et al. (1995), which is stricter than that of Stotz & Krauth (1984) and Pearson et al. (1986), only events which obtain a value in less than 0.185 (area 1) can be designated a first flush. Saget et al., (1995) collected 197 storm data sets from storm and combined sewers in 14 catchments, of these only 1 data set matched their criteria for a first flush. Saget et al., (1995) do not divulge what criteria they used in defining what a first flush is, however it does appear, based on their own data, that the definition may be excessively strict. The structure of the definition, however is in an acceptable form, as the definition is rigid and easily applied. The definition of first flush does appear to be based upon that accepted by Betrand-Krejewski et al. (1993); "when at least 50% of the pollution load are transferred in the first 30% of the (flow) volume".

Although the concentration of the foul flush is largely dependent upon the source material and the characteristics of the storm event, the influence of other factors should not be ignored, these are summarised below;

1. Total volume of DWF.
2. Antecedent dry weather period length.
3. Duration and magnitude of previous storm events.
4. The physical characteristics of the sewers (size, shape, gradient, etc.).
5. At what point during the diurnal pattern the storm occurs.
6. Location of sewer in the system

Krejci et al. (1987) found, in their investigations of small catchments in Switzerland, that storm flow pollutants were made up from five principal constituents, as illustrated in figure, 12a & b.

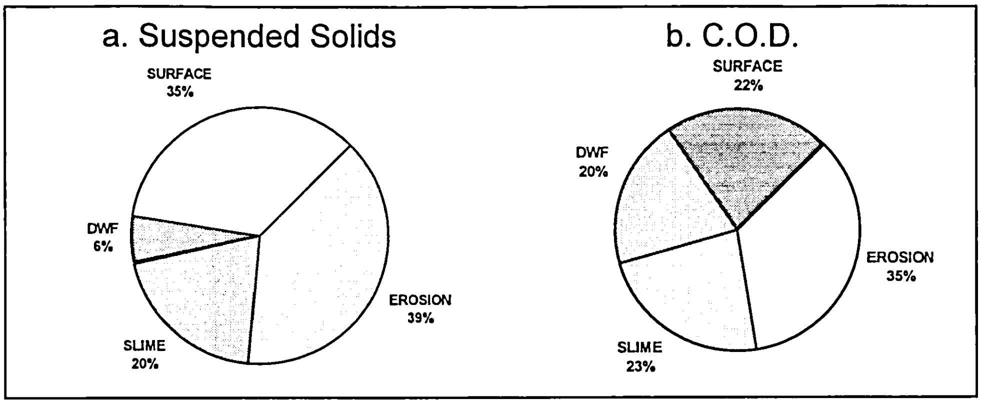

Figure 12a & b : Pollutant Sources (Krejci et al., 1987)

The work of various researchers (Gieger, 1984 & 1987) has questioned whether ADWP plays any significant role in the pollution characteristics of the flush. Geiger (1987) suggests that it has virtually no influence, with a weighting of 1/100. Although a weighting of 35/100 was given to 'unidentified parameters'. Stotz and Krauth, as well as Pearson et al., however found that ADWP was relevant as far as the wash out of material was concerned. From their studies of artificial flushes which entrained only the pollutants from the bed of the sewer, and not the catchment surface, Stotz and Krauth used equation 41, which is in a similar form to that obtained by Saget et al., (1995).

$$y = ax^k \qquad ....41$$

Where: $y =$ The amount of washout material (g/min).

$x =$ The duration of the dry weather period prior to the storm event (h).

$k =$ Time coefficient (dependent on the average bed slope).

$a =$ Site specific constant (0.906).

The results of Saget et al. (1995) do show, however, that there is an increased propensity for foul flushes in storm sewers, from the data collected. Additionally, the data collected also indicated that the intensity of flushes of COD and BOD_5 are more intense than that of suspended solids.

Stotz and Krauth (1984) produced flush events by emptying a ten thousand litre water tank into the sewer system at a constant rate. Generating artificial flushes in this manner means the pollutants in the flow will contain no material freshly entrained from the surface or gully pots. During storms, considerable amounts of material are normally carried into the sewer in this manner, entertainment is usually dependent on the particle size. Studies (Geiger, 1987) have found that not all of this material is transported through the system, but may form sediment deposits.

Saget et al. (1995) linked foul flush with an individual independent parameter This analysis took the form of linear regression of the parameter 'a' against the measured parameters detailed below;

1. Contributing area
2. Time of concentration
3. Sewer slope
4. Rainfall depth
5. Maximum rainfall intensity over 5 minutes
6. The antecedent dry weather period

The researchers found that none of the parameters tested, when considered alone, gave good correlation with 'a', although multiple regression of the parameters is not reported.

Using data collected at Great Harwood by Pearson et al. (1986), Gupta & Saul (1995) obtained relationships which related the pollutant load carried by the foul flush wave ($LOAD_{ff}$), the storm duration (STDURN), rainfall intensity ($RINT_{max}$) and the antecedent dry weather period (ADWP) via multiple regression. The resultant summer (r^2=0.65) and winter (r^2=0.71) relationships are illustrated in equations 42 and 43 respectively.

$$LOAD_{ff} = 1.35 \times STDURN^{0.61} \times RINT_{max}{}^{0.71} \times ADWP^{0.23} \qquad ....42$$

$$LOAD_{ff} = 0.95 \times STDURN^{0.92} \times RINT_{max}^{0.36} \times ADWP^{0.20} \qquad ....43$$

Similar regression analysis was used to examine the peak concentration of total suspended solids (TSS_p), this parameter was shown to be related to the peakedness of each individual storm event (PEAKEDNESS : the ratio of maximum and average rainfall intensity) and the ADWP as shown in equation 44 (r^2=0.77).

$$TSS_p = 123 \times PEAKEDNESS^{0.64} \times ADWP^{0.17} \qquad ....44$$

This relationship does have some resemblance to the work of Coghlan (1995), see section 3.1.2, and also that of Desbordes and Servat, (1984). The relationship obtained by Desbordes and Servat, (1984) is illustrated in equation 45, where $\overline{SS}$ is the mean suspended solids concentration and I_5 is the maximum mean 5 minute rainfall intensity.

$$\overline{SS} = 125.52 + 58.7ADWP + 13.49I_5 \qquad ....45$$

Based on data collected in Dundee (Coghlan et al., 1995 and Coghlan, 1995) a set of site specific relationships have been obtained which have related the temporally varying suspended solids levels during storm events to hydraulic and rainfall parameters. In addition to the site specific relationships obtained, one was obtained which had wider applicability, however it related only hydraulic conditions to the suspended solids level. This work is discussed, in detail, in section 3.2.1.

Although there is some evidence to show that ADWP is related to the build-up of erodible sediment deposits, other researchers have collected data which indicate that it may be linked to the build-up of surface deposits (Ellis et al., 1985). Based on data collected in residential Oxley, Ellis et al. (1985) obtained the relationship illustrated in equation 46 via regression analysis;

$$T_s = 114.86 + 3.589Q + 0.346ADWP + 4.257D_r \qquad \text{....46}$$

Where; T_S = the total solids loading (g/ha)

The work reported on the first foul flush phenomena, and the site specific work relating to storm flow quality indicates that the characteristics of the event may be largely site specific in nature, either relating to surface or in sewer conditions. Each of the relationships proposed by researchers for the prediction of storm pollutant loads rely principally on rainfall hyetographs and the ADWP. The importance of the rainfall hyetograph characteristics has been highlighted by other researchers investigating the pollutant potential of urban runoff events (Geiger, 1984, Jewell & Adrian, 1982 and Lindholm & Aaby,1989).

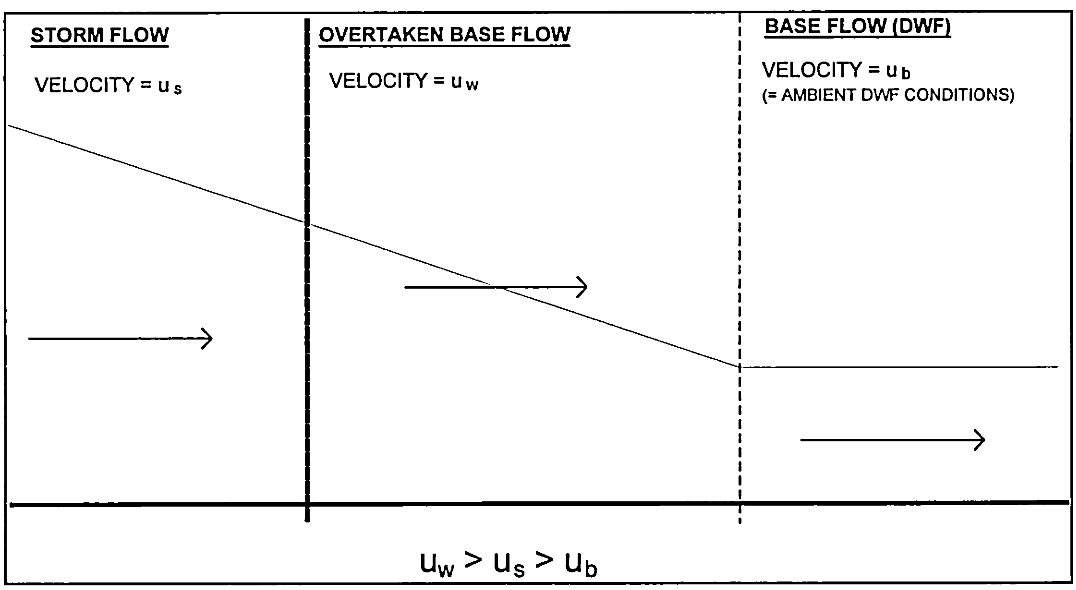

Figure 13 : Idealisation of storm hydrograph
(adapted from Ackers et al., 1968 and Davies, 1990a, 1990b &1996)

Traditionally the source of material for the solids in the first foul flush have been conceived from sewers sediments, surface sediments, gully sediments, pipe slimes etc. However, if a sewer length is considered which has no lateral inputs, a storm wave will move along it as idealised in Figure 13. Using this scenario, it is possible to include near bed solids as a contributing factor to the pollutants associated with first foul flush. The figure represents the storm wave passing a single point in a sewers system, i.e. the x-axis is time.

It is possible to segregate the storm wave into 3 discrete sections each with a different ambient velocity;

u_w = The mean wave speed, generated by the storm inflow.

u_s = The mean velocity of the storm water

u_b = The mean velocity of the base flow

The section of level flow consists of normal DWF, or 'baseflow', travelling at ambient DWF velocity. The front part of the storm wave proper will consist of overtaken baseflow, i.e. DWF which is "forced" to travel faster then normal due to the inflow of storm runoff. In experiments, using a saline baseflow, Harrison and Holmes (1967) observed negligible dispersion of pseudo storm water mass into the overtaken baseflow. This is idealised by the thick dashed vertical line which separates the 2 zones in the figure. The area between the storm flow and baseflow represents the volume of overtaken base flow. In this overtaken baseflow the velocity conditions are increased, this will then result in any deposited solids being eroded into the flow column, and thus increasing the suspended solids level to above ambient DWF levels. The solids in the main storm flow will then consist of baseflow, solids from the surface, and gully pot sediments, which have all been diluted by the storm runoff. Clearly the representation of first foul flushes by Ackers et al. (1968), Davies (1990a, 1990b &1996) and Harrison & Holmes (1967) is simplistic but it does give a clear definition of the phenomena. Any material moving at the bed can, implicitly, be in included in the first foul flush solids using this approach. This material could be added as it would be entrained just before any deposited sediment bed is eroded. This approach to explaining the influence near bed solids has on first foul flush has potential for development in analysing the results from the current project.

Although these assumptions may appear over simplistic, this approach is the basis for designing storage overflows (Ackers et al., 1968), which was aimed at retaining only the first flush portion of the storm hydrograph. The concept has also been used in the analysis of experiments relating to the overtaken baseflow, by injection of particles by Davies (1990a, 1990b and 1996). Davies found that the concentration of suspended solids in the overtaken baseflow was equal to that in the baseflow for suspended solids transport.

2.7 Discussion

The work reported in this chapter has demonstrated the wealth of research investigating solids transport in rivers, estuaries and sewers. The large variations in the observations presented highlight the need for research in this field. Section 2.1 "Introduction" gave an overview of the hydraulic and pollution problems associated with sediments in sewers, and highlighted the main sources of sewer sediments experienced extensively in the U.K.. The basic mechanics of sediment erosion and transport were discussed in Section 2.2 "Flows". Section 2.3 "Sediment Characteristics" gave details of the large variations in the solids in transport and deposited in sewers in the U.K..

Section 2.4 "Sediment Transport" defined the different modes of transport in sewers. The transport of sediment as "bed-load" in sewers was discussed, and for the purposes of this study the mode of transport was termed *Near Bed Solids* (NBS) transport.

The influence bed-forms have on flow conditions was detailed in section 2.5 "Bed-Forms". The different definitions of the first flush phenomena were compared. In section 2.6 "First Flush" various characteristic which researchers have proposed as influencing first flushes are highlighted. The work presented dealing with foul flush phenomena has illustrated the need for a concise definition which can be widely applied. The intensity of foul flush events, and storm pollutographs, has been shown to be dependent on catchment characteristics, the rainfall hyetograph and the antecedent dry weather period. The use of the ADWP in predicting storm pollutant concentrations may represent the upstream sediment bed characteristics (where present) or the build-up of surface deposits, as both surface and sewer sediments will become increasingly established during dry weather periods. The parameters highlighted by the researchers in this area will be tested using the data collected in the current project.

A simplistic approach proposed by Ackers et al. (1968), Davies (1990a, 1990b &1996) and Harrison & Holmes (1967) may be applied to explain the contribution of near bed solids to the pollutant intensity of first flushes, and is stressed as being particularly significant to this study.

Chapter 3 : Fieldwork Studies Related To This Project

Over the past 10 years there has been a considerable amount of research investigating sewer sediment in real sewers, as illustrated in the previous chapter. This chapter seeks to report the concerted fieldwork programmes which are relevant to this study. The data collection and analysis methods and subsequent results are reported with equal importance as the main conclusions of these studies reported often contain a great deal of subjectivity.

The work undertaken in Dundee is given emphasis in this chapter as much of this work has formed the basis for the current project.

3.1 Dundee

The Dundee central area sewer network has, historically, suffered from sedimentation problems, this combined with extensive flow control facilities (over 250 manually operated gates) has made the sewerage system a centre for intensive data collection and research over the past ten years or so. The studies undertaken in the system are impressive in terms of both number and variety. In terms of this study, the two most pertinent studies undertaken are those reported by Wotherspoon (1994) and Coghlan (1995). In this section, only cursory details will be given concerning the Dundee central area catchment and its sewerage system, as an overview of the system is given elsewhere (Chapter 5.0), and is described in some detail by other authors (Ashley et al 1992, Ashley 1993b, Ashley 1994, Wotherspoon 1994, Coghlan 1995 and Rennet 1995).

The main programme of field work undertaken by Wotherspoon (1994) and Coghlan (1995) was based in a 175m length of the interceptor sewer in Dundee City Centre. The interceptor, at this point, drains an area of 340 hectares and serves a resident population of approximately 37000. The average gradient of the sewer in the study length is 1:1450 (0.69‰) and is straight in alignment. The sewer has a maximum size of 1.755m wide × 1.415m high (non-standard egg section, with a Vee shaped invert).

3.1.1 Wotherspoon (1994)

The research reported by Wotherspoon (1994) recognised that sediment transport studies in laboratories have concentrated on the movement of essentially non-cohesive sediments, whilst in practice sewer sediments can exhibit cohesive-*like* characteristics (although sewer sediments cannot be said to be cohesive in the classical sense). So with the aim of quantifying the apparent cohesive nature of sewer sediments, and their erosional behaviour, Wotherspoon (1994) undertook a field programme. Based on this work an empirical model was constructed which could predict the availability of sediments for erosion, and it is this work which is summarised here.

3.1.1.1 Rheological Testing

Based on fundamental studies by Williams et al. (1989), Williams and Williams (1987) and Kirby (1988), Wotherspoon (1994) assumed that sewer sediments can demonstrate elastico-viscous properties and that the steady shear methods used by geotechnical engineers to determine yield strength are not appropriate due to the heterogeneous nature of the material. Based on these assumptions Wotherspoon (1994) was able to select a method to test the yield strength of sediments using the direct shear stress and shear wave propagation techniques via a cruciform vane geometry, which assumes a cylindrical failure surface, which causes the sample to fail via creep deformation.

A total of 61 tests were carried out, using a controlled stress rheometer. Samples were also tested for volumetric solids (V_s), moisture content (m), bulk density(ρ), voids ratio (e) and particle size distribution (d_{50}). In analysis of the data, linear and multiple regression were undertaken in an attempt to determine if any of the measured physical parameters had an affect on yield strength. Based on this analysis the equations 47, 48, 49, 50 and 51 were obtained.

$$\tau_y = 2.5728\exp\left(10.9105V_s\right) \quad (r^2 = 0.802) \qquad \text{....47}$$

$$\tau_y = 1.71 \times 10^{-37}\rho_s^{12.2671} \quad (r^2 = 0.592) \qquad \text{....48}$$

$$\tau_y = 9.66 \times 10^{7}\,m^{-3.1682} \quad (r^2 = 0.920) \qquad \text{....49}$$

$$\tau_y = 6.37 \times 10^{2}\,e^{-2.5707} \quad (r^2 = 0.848) \qquad \text{....50}$$

$$\tau_y = 3.86 \times 10^{-15}\rho_d^{5.6221} \quad (r^2 = 0.867) \qquad \text{....51}$$

Wotherspoon (1994) found that of all the measured parameters, moisture content provided the best correlation with yield strength, $r^2 = 0.920$, and this was proposed as the predictor relationship. The researcher does recognise, however, that the degree of experimental error involved in determining the other physical characteristics (V_s, m, ρ and e) may be significant. This is mainly due to the small volumes of sample involved (typically ~50ml). It should also be noted at this stage that in calculating the moisture content the standard geotechnical method (BS 1377, 1975 and Craig, 1987) is used (equation 52) and in doing so it is possible to obtain moisture contents in excess of 100%.

$$m = \frac{M_w\text{, Mass of Water}}{M_s\text{, Mass of Solids}} \qquad \text{....52}$$

3.1.1.2 Erosion Monitoring

It was possible to measure sediment erosion and deposition at a single point in the interceptor sewer using specially developed instrumentation. The instrument used comprised of a pivoted arm fixed to the roof of the sewer, with a sonar transmitter/receiver head fitted to the other end. A digital inclinometer was fitted to the pivot so that the angle of the arm could be determined. The sonar head was allowed to float on the surface of the flow, and transmitted sonar signals toward the invert at predetermined intervals, the signal is then reflected from the invert (or sediment bed if present). Based on the time between the transmission and reception of the sonar signal the depth of water over the sediment bed can be determined. The distance between the water surface and the crown of the sewer can be determined using the information from the inclinometer. Based on this data the depth of any sediment bed can be calculated, given the sewer diameter.

Due to the prototype nature of the device only intermittent results were obtained, and it was not possible to obtain data relating to the long term build-up of sediments in the study area. However, data were obtained which showed partial erosion, and deposition, during DWF. Additionally data from a number of storm events appearing to show bulk erosion of sediments were obtained. In summary the following conclusions may be made concerning the data obtained from the sonar device;

1. Erosion can occur at the peak in DWF, although this may be dependent on the physical characteristics of the sediment.
2. Storms erode sediment formations significantly.
3. Where a sediment bed erodes during storm events it is quickly re-established to near the original depth.
4. Bulk erosion of the bed is initiated when bed shear stress exceeds 1.5-2.0 N/m^2. This confirms the findings of Alvarez (1992) in laboratory studies, and Stotz and Krauth (1986) in the field.
5. The device appears to detect a small increase in bed depth prior to some erosion events, and Wotherspoon (1994) infers that the device may be detecting a first foul flush event.

The observations regarding the rapid reformation of the sediment bed after storms is corroborated by the findings of Laplace et al (1990 & 1992), who found that once the sediment bed had reached an equilibrium level the overall effect of rainfall became less important.

Based on the rheology results, the data obtained from the sonar device, and the measured physical characteristics of the sediment deposits found at the study site, Wotherspoon (1994) was able to formulate a model which could be used to estimate erosion, and to some extent deposition, in the sewer length studied. The basis for the model was an existing relationship developed in estuarine studies (Mehta and Partheniades, 1982) which relates density to depth within a deposited bed. This relationship is shown in equation 53.

$$\frac{\rho_d}{\rho_s} = \zeta\left(\frac{Z'}{y_s}\right)^{-\xi} \qquad \text{....53}$$

Where: ρ_s = Density at depth Z

ρ_d = Dry density

y_s = Bed thickness

Z' = y_s - Z

ζ = Dimensionless coefficient which controls erodibility

ξ = Dimensionless coefficient which controls density

This relationship has also recommended for use by Torfs (1995) in a study investigating mud/sand consolidated sediment mixtures. In utilising this relationship, Wotherspoon (1994) hypothesises that the sediment bed comprises of a number of finite layers each with a clearly defined yield stress, moisture content and bulk density. Each of these layers, therefore, will not erode until the bed shear stress, τ_b, exceeds the yield strength, τ_y, of the layer concerned. Hence erosion occurs, to some extent, when $\tau_b \geq \tau_y$.

Using the relationship which was obtained from the rheological testing, equation 54, it is possible to estimate the moisture content of the layer considered. The density of the erodible material may then be calculated using equations 55 and 56 (Craig, 1987).

$$\tau_y = e^{18.3865} m^{-3.1682} \qquad \text{....54}$$

$$\rho_e = \frac{s\rho_w + e\rho_w}{1+e} \qquad \text{....55}$$

$$e = m.s.g \qquad \text{....56}$$

Assuming a specific gravity of 2.6, the original Mehta and Partheniades (1982) relationship may then be represented in the form shown in equation 57.

$$y_e = y_s - \left[y_s \left(\frac{\rho_e}{\zeta \overline{\rho_o}}\right)^{-1/\xi} \right] \qquad \text{....57}$$

Where: $\overline{\rho_o}$ = Average initial bed density

ρ_e = Erobible density

y_s = Initial average bed depth

y_e = Erodible depth

Using the coefficients, ζ and ξ, this relationship was then calibrated from the erosion data obtained from the sonar device. This calibration is carried out before the storm when the depth of the sediment deposit remains relatively constant (in equilibrium). The coefficients, ζ and ξ, varied from 0.65 - 0.70 and 0.2 - 0.5 respectively. The application of the model is best illustrated by means of a flow diagram, as illustrated in Figure 14.

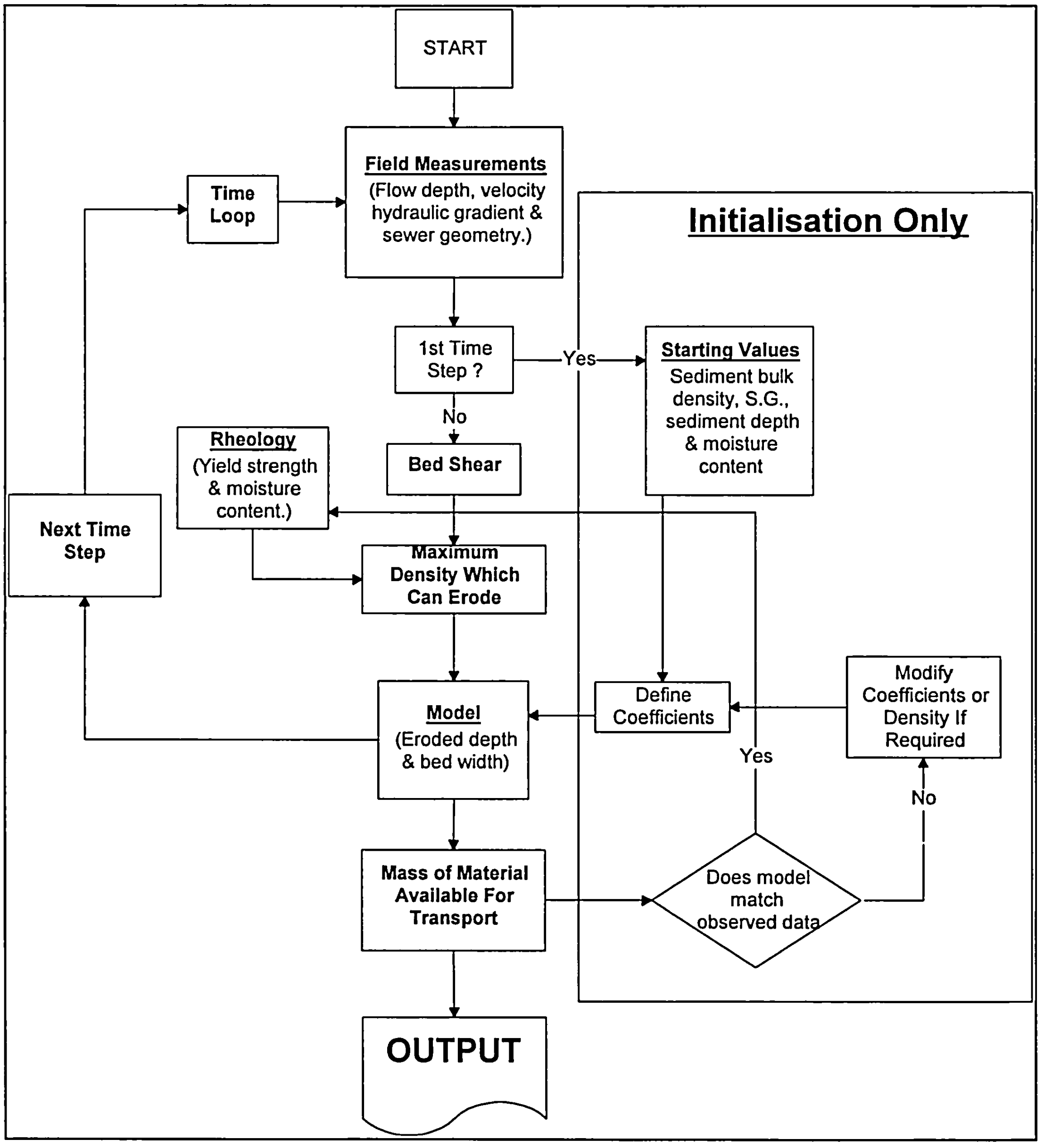

Figure 14 : Application of the model proposed by Wotherspoon (1994) (adapted from Wotherspoon,1994)

3.1.1.3 Summary of Work

The work of Wotherspoon (1994) represents a comprehensive study of cohesive-*like* sewer sediment characteristics, and their erosional behaviour. However, the analysis procedure is best applied only to the type of sediment found in the study area (i.e. low median particle size and low organic content).

With regard to the yield strength relationship obtained via the rheological analysis, although moisture content clearly shows good correlation with the yield stress it is difficult to believe that it is the sole parameter involved. Other parameters, such as density or organic content must be important, although moisture content must be related to these parameters. Beyer (1989), found that organic content was an important factor in the development of yield strength in sewer sediments.

Additionally, although the development and the use of the sonar device to monitor sediment deposition and erosion in sewers does represent significant progress in in-sewer instrumentation, the results obtained are open to some degree of scepticism. As the device was used to monitor erosion events where, typically, less than 5mm of material was eroded from the bed, when the accuracy of the unit is known to be ± 5mm. Additionally it is not clear under what conditions the sonar wave will not be reflected, i.e. as the density of the bed approaches that of water the performance of the device must drop. Additionally, the instrument, as employed by Wotherspoon (1994), is known to have a significant 'footprint' during changes in depth. These problems are undoubtedly due to the prototype nature of the device, and with further development it will provide an essential research tool.

3.1.2 Coghlan (1995)

Coghlan (1995) recognised that the accurate prediction of solids transport in sewers is a problem which has been addressed by a number of laboratory and field studies, none of which have been entirely satisfactory. Based on this a research programme was initiated, with the aim of obtaining a method for the accurate prediction of solids transport in sewers. Specifically the relationship sought was to have the ability to predict suspended solids concentration variation with time (pollutograph), given a limited amount of physical and hydraulic data.

3.1.2.1 Model Development

Development of the sediment transport relationships obtained by Coghlan (1995) can be summarised in the steps listed below;

1. Collection of data regarding sediment transport, both in suspension and at the bed. (what Coghlan (1995) termed bed-load).
2. Examine the models obtained by other researchers, and attempt to calibrate them using the field data collected.
3. If step 2 does not produce a good predictive relationship, develop an independent site specific empirical model to predict sediment transport at the principal (Dundee interceptor sewer) site.
4. Develop a second site specific model based on the data obtained from a validation site (Perth Road trunk sewer in Dundee).
5. Attempt to link the two site specific relationships to construct a more universally applicable model.

In model calibration, the stated aim of the researcher was to obtain a model which could predict sediment concentration in the range illustrated in equation 58:

$$\frac{\mathrm{TSS_{OBS}}}{2} < \mathrm{TSS_{CALC}} < 2\mathrm{TSS_{OBS}} \qquad \text{....58}$$

Where TSS_{OBS} is the observed sediment concentration and TSS_{CALC} is the predicted. This apparently wide margin of error allows for all the inherent uncertainties involved in field data collection, and corresponds to typical fluvial hydraulic criteria (White et al., 1975).

3.1.2.1.1 Data Collection

Data were collected from two sites in a 175m stretch of the interceptor sewer, the first being approximately 200m downstream from its head. Additional data, for validation, was collected from one site in the Perth Road trunk sewer. Parameters directly measured were flow depth, flow velocity, ADWP, TSSS (Time Since the Storm Started) along with the physical characteristics of the sewer and its sediment deposits. The data were measured simultaneously at the two interceptor sewer sites, and independently at the validation site. In association with this data, sewage samples were obtained, and tested for TSS only.

In addition to the work undertaken monitoring suspended solids concentration in the study areas, a rudimentary attempt was made to quantify the material moving at the bed in the interceptor sewer (McGregor & Ashley, 1989 & Coghlan, 1995) in order to obtain a more complete picture of the materials moving in the interceptor sewer at any given moment in time. To collect samples of this material a temporary wooden flume was constructed over a silt trap at the head of the interceptor, similar to the installation described in section "5.3.2 Study 2 Samuels Silt Trap" Interceptor Sewer. A series of sediment traps were installed in the invert, towards the downstream end of the flume. When samples of material moving at the bed were being obtained, simultaneous sewage samples were also retrieved. A summary of the data obtained is illustrated in Table 7 (from Ashley, 1993).

The average rate of solids transport was found to be approximately 3.7 g/hd (~0.640g/s), with a maximum of 9.8 g/hd (1.696 g/s), in comparison with 28 g/hd (4.845 g/s) for suspended solids. Based on this data, it was estimated that suspended solids, on average, account for some 88% of the total solids in transport (Ashley et al, 1992). The data collected were not sufficient to develop a transport model which related specifically to this material. With this in mind Coghlan (1995) assumed the 88% : 12% partition remained constant at all times.

TABLE 7 : NEAR BED SOLIDS CHARACTERISTICS, From Ashley (1993b)

	Bulk Density (kg/m^3)	Total Solids (%)	Volatile Solids (%)	COD (mg/l)	Ammonia (mg/l)	BOD (mg/l)
AVG	1070	4.7	76.0	180821	137	46398
MAX	1448	2.9	97.4	336356	571	71846
MIN	972	50.2	14.7	54591	34.2	16833
No.	63	63	58	38	37	32
SD	79	9.67	17.9	17.9	109	16361

3.1.2.1.2 Application of Existing Models

The first stage in the analysis of the field data was to assess the performance of existing transport methodologies. In selecting models suitable for application to the data collected, Coghlan (1995) recognised that a number required significant amounts of data pertaining to parameters which are difficult to obtain in the field. As the data collection undertaken by Coghlan (1995) was limited, this restricted the models which could be considered, the models selected were;

Ackers (1984)

Sonnen and Field (1977)

As not all the data were available for the operation of these models, it was proposed that they could be calibrated using the unknown parameters. The unknowns for the Ackers (1984) method being the specific gravity and particle size of the suspended material, whilst the particle settling velocity was also required for the Sonnen and Field (1977) relationship. As the aim of this procedure was to calibrate the model, it was recognised that the values obtained for the unknowns would not necessarily be realistic.

The DWF and storm calibration procedures for the Ackers (1984) model obtained the values for the unknowns illustrated in table 8, where $X = TSS_{OBS}/TSS_{CALC}$.

Application of the Sonnen and Field (1977) model, by Coghlan (1995), was not as successful, and as a result the method was abandoned.

TABLE 8 : ACKERS (1984) CALIBRATION RESULTS FOR SUSPENDED SOLIDS TRANSPORT, From Coghlan (1995)

	DWF	STORM
S.G.	1.0137	1.000285
d_{35} (m)	0.0008	0.02
$\frac{1}{2} < X < 2$	68.8%	68.8%

The next stage in the analysis of the data obtained was to apply a rating curve methodology based on the flowrate, the relationship obtained is illustrated in equation 59.

$$TSS_{DWF} = 955Q^{0.8} \qquad \text{....59}$$

Using this relationship, 82.6% of the data were found to fit in the range $\frac{1}{2} < X < 2$, significantly better than that obtained using the Ackers (1984) model, and this relationship was far simpler to apply. However, no relationship could be obtained with regard to the storm data as, the researcher assumed, TSS did not vary with flowrates during storms.

This finding appears to indicate that the discharge parameter, in this relationship, represents domestic and industrial inputs to the system to some extent. This would explain why during storms flowrate is not an important predictor, where most of the inputs, in the initial stage of the storm duration, will originate from the rainfall event.

The final tool which was used in the analysis of the data was to apply multiple regression to the parameters involved, with the methodology employed as listed below;

1. Regress TSS, as an independent parameter, against each of the dependent variables in turn.
2. Rank the independent variables in accordance with the resultant r^2 value and standard error, in accordance with a methodology employed by Pisano & Quieroz (1977).
3. Evaluate the resultant equation using TSS_{OBS}/TSS_{CALC}.

Based on this methodology all the relevant parameters were considered, and equations 60 (same as the relationship using the rating curve approach) and 61 resulted for DWF and storm conditions respectively.

$$TSS_{DWF} = 955Q^{0.8} \qquad ....60$$

$$TSS_{STORM} = 104.4 + 416.4V - 0.8TSSS - 3.124ADWP \qquad ....61$$

Using these relationships 82.6% and 78.3% of the data were found to fit in the range ½ < X < 2 for the DWF and storm data respectively. Clearly the relationships generated from the regression analysis of the interceptor sewer data have resulted in the most reliable of the methods tested. As this method was the most successful, it was this that was first applied to the validation data, equations 62 and 63 resulted.

$$TSS_{DWF} = 1930Q^{0.48} \qquad ....62$$

$$TSS_{STORM} = 769.1 + 9134Q - 1661.7d - 1162V - 0.6247TSSS \qquad ....63$$

Using these relationships 80.6% and 95.9% of the data were found to fit in the range ½ < X < 2 for the DWF and storm data respectively.

Coghlan (1995) then made an attempt to link the site specific models obtained, with the aim of generating a relationship which could be applied to either of the sites, or conceivably further afield. In an attempt to introduce differences between upstream sewer condition the 'DAS' factor proposed by Ashley et al (1992) was utilised. The DAS factor was originally formulated for use in sewer classification, as illustrated in equation 64;

DAS = Pipe **D**iameter (m) × Catchment **A**rea (ha) × Pipe **S**lope^{-1} 64

The resultant DAS factor is then used to distinguish between sewer types;

	DAS	< 6	Collector Sewer
6 <	DAS	< 8000	Trunk Sewer
8000 <	DAS		Interceptor Sewer

The inclusion of the DAS factor resulted in improved model performance for the relationships obtained, 80.6% and 78.2% of the data were found to fit in the range ½ < X < 2 for the DWF and storm data respectively. The relationships are shown in equations 65 and 66. The latter equation appears to indicate that, for the data collected, during storms hydraulic condition are the most important factor.

$$TSS_{DWF} = 2.47 \times 10^{4} \times Q^{0.55} DAS^{-0.45} \qquad ....65$$

$$TSS_{STORM} = 42 + 272.3V \qquad ....66$$

3.1.2.2 Summary of Work

If the best model, for a given purpose, is that which requires minimal data collection and operates well over a wide range of conditions, then clearly the work of Coghlan (1995) represents a significant step in suspended sediment transport. It is unfortunate, however, that the models generated do not address the fundamental mechanisms involved in the transport process.

Additionally, practitioners would have been aided a great deal if the data obtained had been applied to a wider range of existing models, so that they may have been evaluated. Of notable omission is the model proposed by Macke (1982 & 1983) (equation 67) which appears to be applicable to the data collected, and is being proposed as a basis of the criterion for suspended sediment transport in sewer design (Ackers et al., 1994 and Butler et al 1995a and 1995b).

$$Q_{s*} = Q_s \rho g(s-1) w_s^{1.5} = 1.64 \times 10^{-4} \tau_o^3 \qquad \text{....67}$$

It is also notable that bed shear does not appear to have been included in the regression analysis.

It is significant that in the regression analysis of the storm data Coghlan (1995) obtained from the validation site ADWP was found not to be important, whilst the parameter was found to be of importance in the interceptor data. It is not clear if this parameter represents sediment build-up on the surface or in the sewer, or perhaps both. This situation, regarding the Dundee data, may be partially explained when the nature of the in-sewer sediments are compared. In the Perth Road, sewer sediments were found (Ashley, 1993b) not to be significantly affected by rainfall events, and are quite coarse in nature ($d_{50} \cong 1.2$ - 10.0mm). Whilst in the interceptor, sewer sediments are known to erode in even quite insubstantial rainfall events (Wotherspoon, 1994) and are much finer ($d_{50} \cong 400\mu m$). Clearly sediments which build up in the interceptor sewer during the ADWP are readily erodible, subsequently much of the eroded material is of a size which is readily carried in suspension (by storm flows), whilst the same may not be true of the Perth Road sediments.

Other studies have encountered problems in quantifying the affect of ADWP as illustrated in section "2.6 First Flush". Based on this work it appears that inclusion of ADWP in the regression analysis may represent the build-up of partially erodible in-sewer sediments during dry weather. However, clearly more work is required in this area. If the importance of ADWP is to be confirmed.

3.2 Belgian Sewer Sediment Research

A considerable amount of work on the pollution aspects of sewer sediments has been undertaken in the sewers of the Belgian capital, and elsewhere, by Verbanck (Verbanck, 1990, 1992, 1993, 1994, 1995a, 1995b & Verbanck et al., 1990). This work has been based in a 4m diameter sewer some 5.4 km long, of an average gradient of 0.025‰, which drains an area of 3520 hectares (60% impervious) and serves a population of approximately 380,000. The average velocity and discharge in the sewer is 0.5m/s and 0.5m^3/s respectively. The main emphasis of the work in Brussels has been to investigate the nature of solids in sewers, both those which are in transport and those which have been deposited.

Based on measurements obtained from in-situ turbidity meters (Vanderborght & Wollast, 1990) and sewage sampling, the Brussels researchers have been able to estimate a total suspended solids transport rate of 36,585 kg/day for weekdays and 19,461 kg/day for weekends. Verbanck hypothesises (Verbanck, 1990) that there is the same amount of material entering the system at weekends as week days, but due to the normal diurnal variations in flow patterns (i.e. typically lower average velocities at weekends during dry weather flow) this material deposits (~17 tonnes per day) over the weekend.

As suspended solids concentrations were monitored continually, using turbidity meters, at the outlet of the Brussels sewer a substantial amount of data are available concerning the first foul flush phenomena (Verbanck, 1990). Storm data collected shows two distinct suspended solids peaks at the onset of the event pollutograph, the first being highly organic and the second being mainly inorganic. The Brussels data also indicates that suspended solids concentrations during storms are affected by antecedent dry weather period. This confirms the findings of Stotz and Krauth (1984), Coghlan (1995) and Gupta and Saul (1995). For the data collected in the field Verbanck hypothesises the preceding storms may have a leaching effect on the sewer sediments, however the same effect on the surface sediments is not considered.

Particle size distribution analysis of sewer sediments obtained from the Brussels sewers indicates the material has a d_{50} of 200-500 μm, and the material is seen to be non-uniformly graded, with few particles below 125 μm. Verbanck postulates (Verbanck, 1990) the particles below 125 μm may be elutriated from the bed by the daily peaks in dry weather flow.

Data have also been collected in Brussels, (Verbanck et al., 1990) which deals with the particle size characteristics of material carried in the suspended mode during both DWF and storm conditions. This was done by sieving the particles in the size range 0.045mm - 2.0mm, the pipette method then being used for particles below 45 μm. Particles greater than 2mm were excluded from the analysis. It was found that the solids transported in the suspension phase were mainly inorganic (~60-80%), and typically 63% were finer than 45μm (dry weight). Data were also presented which show how organic content varied within each size fraction. The data indicated that, for storm samples, the organic fractions of the suspended sediment was not uniformly distributed throughout each of the size fractions. At each end of the size ranges organic levels are seen to be as high as 70-80%, whereas levels fall to 10-15% in the intermediate silt range. However, when data are interpreted in terms of total mass the distribution is seen to be reasonably uniform. DWF data show a shift to a suspended sediment which is higher in organic content. Based on this data Verbanck et al. (1990) hypothesise that the higher inorganic levels in the storm sewage samples is due to erosion. However as the particle size of the mineral fraction of the suspended sediment sample is not consistent with that of the in sewer sediment deposits, the Belgian researchers assume that the material is liberated from areas which are considered to be 'protected' from normal DWF conditions (i.e. benching, walkways etc.). However, the possibility that the source of this material may be the wash-off of surface deposits caused by the storm events is not considered.

After the work dealing with particle size distributions within the suspended solids transport phase, Verbanck (1993) then went on to investigate how particle characteristics varied with depth during DWF. A 'snapshot' of the suspended solids profile was obtained over 30 minutes, and were obtained via a small bore (8mm internal diameter) sampling hose. Simultaneous velocity distributions were also obtained.

A distinct suspended solids profile was observed, which was the inverse of the flow velocity distribution. It was found that the profile was most distinct when the hydraulic gradient was low and the sewer was straight. Material sampled in transport near the bed was found to be highly organic and highly concentrated (up to 5g/l). As this material was highly organic, and consequently low in specific gravity, Verbanck (1995) hypothesises that this material may quickly move higher in the water column after only a small increase in ambient velocity (and hence bed shear). Therefore this highly organic material moving near the bed will play an important role in first foul flush. The suspended solids profile observed is illustrated in Figure 15. This figure illustrates how there is little evidence for the sharp increase in solids concentration at the bed for the Brussels data presented.

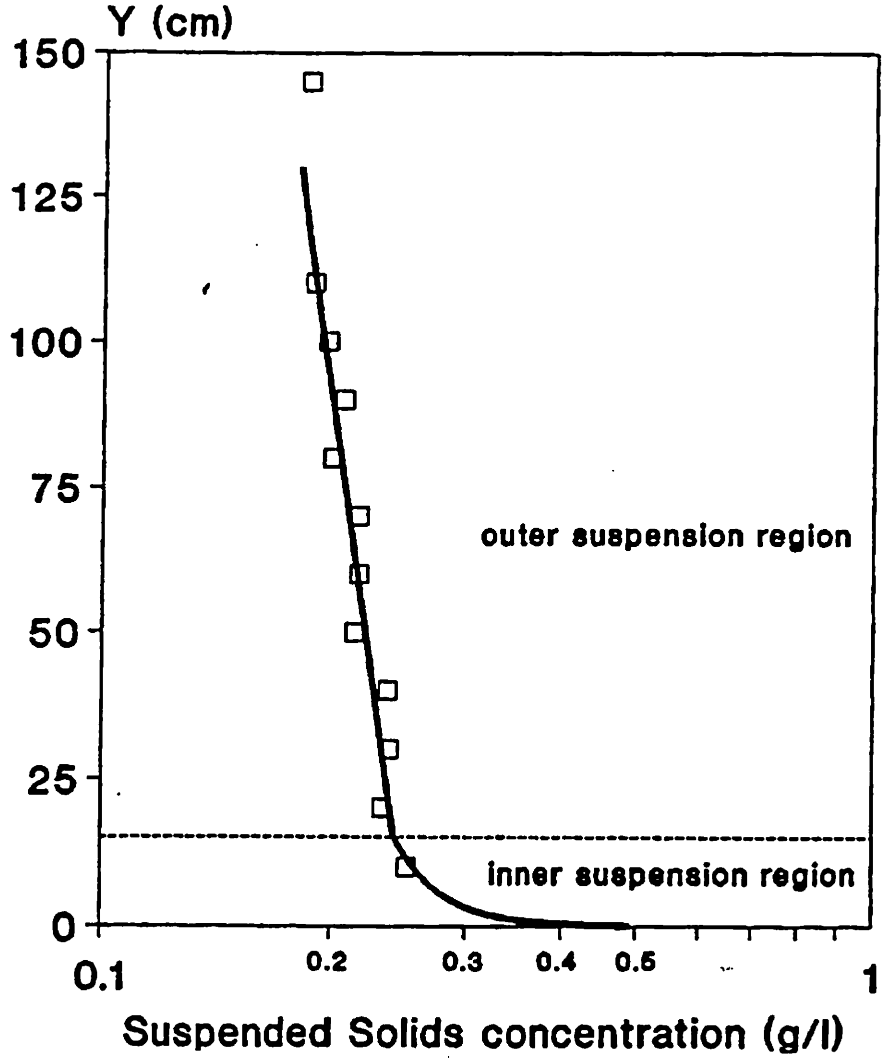

Figure 15 : The implied Brussels suspended solids profile (from Verbanck, 1995a)

Using the data relating suspended solids concentration with depth, Verbanck later (Verbanck, 1994) divided the water column into two distinct zones; an *outer suspension region* and *inner suspension region* (or *dense undercurrent*). The data collected by Verbanck (1995a) shows a moderate increase in suspended solids concentration near the bed. Verbanck, however, believes that near the bed the suspended solids concentration increases considerably. Data are presented which indicate that suspended solids concentration, particle weight and mineral content all increase significantly near the bed when only particles greater than 0.5mm are considered. It was found that material being transported in this region was highly organic (typically >90%), and consequently low specific gravity. The Belgian researcher hypothesises that it is the size of these highly organic solids which causes them to settle into his dense undercurrent, despite their low specific gravity. Once in the inner suspension region Verbanck believes that the steep velocity gradient, and associated turbulence, near the bed prevents them from finally settling on the bed. Davies and Samad (1979) observed in laboratory studies that particles near the bed may be subjected to negative lift, which may result in settlement, when flows are hydrodynamically smooth ($R_* < 5$) and where there is flow moving through the bed itself.

The Belgian sewer sediment research programme has culminated in the adoption of the work of Bagnold (1966) to produce a tentative site specific methodology for the determination of the transport capacity of the flow in the cunette shaped sewer in Brussels. The procedure employed is based on the relationship illustrated in equation 68;

$$C_v = \frac{1}{5.16} \times \frac{u_{*,b}^3}{\rho_w g(s-1) w_s R} \qquad \text{....68}$$

Where w_s is estimated using equation 69;

$$w_s = \sum_i \left(p_i \sqrt{\frac{13.95\nu}{d_i} + 1.09(s-1)\rho g d_i} - \frac{13.95\nu}{d_i} \right) \qquad \text{....69}$$

Where d_i is the particle size of the sediment fraction considered.

Only limited data are presented, which relate to a severe storm with a long ADWP (25 days) however the relationship does perform well until the flow level reaches half the conduit height. Verbanck (1995b) suggests that this is due to the presence of a walk way at this height, from which a limited amount of fine sediment is eroded.

Although Verbanck has collected a considerable amount of data to support his dense undercurrent hypothesis it is difficult to ascertain if the samples obtained near the bed using a small bore sampling tube (internal diameter 8mm) were truly representative of the material being transported there. Additionally, where solids are sampled just above a deposited bed using vacuum samplers the possibility of sampling some bed material cannot be discounted. The methods employed by other researchers (Ashley et al., 1993b and Lin et al. 1993a & b) may be better suited for collecting larger solids moving along the bed, although these methodologies may not collect material moving in suspension just above the invert.

3.3 French Sewer Sediment Research

In France, a research programme was established to investigate solids in sewer systems, and their interaction with other pollutants. The initial aims of the programme were (Chebbo, et al., 1990):

1. To determine the ability of solids to be deposited or eroded by the flow in trunk sewers.
2. To categorise solids with regard to pollutant potential.

The work was undertaken in several catchments, and sewer types, as illustrated in Table 9. Much of the work was carried out in the No. 13 trunk sewer in central Marseille, which drains an area of some 134 hectares, with 85% impermeability. Surface water drains into the sewer via non-separating gullies.

The research programme began with the characterisation of solids transferred into sewers during DWF and storms, with the emphasis being placed on the latter. The researchers found that particles transported in suspension were predominately fine (d_{50} = 30 - 38μm & d_{70} < 100μm). The data collected also indicated that there was little difference in suspended sediment characteristics between catchments, even where they were in different towns. It was also found that the particle size distributions did not vary between storm and DWF, although other characteristics did change (density and settling velocity).

TABLE 9 : FRENCH DATA COLLECTION SITES

Site No.	Site	Sampling Methods
End Of Sewer System		
1	Bequigneax, Bordeaux Storm Sewer.	Auto. sampling at different levels
2	Perinot, Bordeaux Combined Sewer.	Auto. sampling at different levels
3	Les Brouillards, Seine St. Denis Storm Sewer.	Manual sampling
4	La Molette, Seine St. Denis CSO.	Sediment sampling
In the Sewer System		
5	Sewer No. 13, Marseille	DWF, auto. sampling & sediment sampling
6	Trunk Sewer No. 13, Marseille	DWF, auto. sampling
7	Bordeaux Storm Sewer.	Storm, manual sampling
Entrance to Sewer System (Gullies)		
8	Toulouse, Motorway & Residential Area	Storm, first 30 litres
9	Marseille (Residential Street)	Storm, first 30 litres

The work dealing with particle size distributions of suspended sediments was later extended to include characterisation of the pollutant and hydrodynamic characteristics of solids transported in sewers during dry and wet weather (Chebbo et al., 1990). Data collection for this work was carried out in the same catchments as earlier. However, comprehensive measurement and sampling techniques were only used at the Bequigneax settling basin, at the remaining tanks average storm flow characteristics were determined using samples of the outflow and the sediment deposited in the tanks during sampling. The main conclusion of this work was that during storms the median particle size (~20 - 27μm) did not vary greatly between catchments for particles less than 50μm. Settling velocities of particles smaller than 50μm were found to be high, 66% > 2.5 m/h (0.69 mm/s), with 70 - 80% of particles settling within 15 minutes, and 97% within 1 hour. It was also found that during storms the settling velocity of the suspended particles was higher than during DWF conditions. The researchers hypothesised that this was due to changes in the physical characteristics of the particles in suspension caused by an increase in the ambient velocity conditions.

Analysis of the pollutant characteristics of the sewage samples obtained indicated that the pollutants were primarily associated with the solid phase (75 - 90% total COD, 80 - 85% total hydrocarbons).

To augment the work undertaken dealing with the pollutant characteristics of suspended sediment, work was initiated to investigate where in sewer networks sediment is most likely to be found, and which factors influence sediment deposition. This work was carried out in several different catchments, namely; Marseille, Montreuil-Sous-Bois and Paris (Bachoc, 1991).

Comprehensive field surveys where undertaken investigating sites where sediment deposits were found, the amount found there and its characteristics. It was found that most sediments were found in sewers with low invert gradients, with 95% of deposits in sewers with invert slopes <10‰, and 65% in sewers with a slope <5‰. In conjunction with low invert gradients additional conditions where sediments were found to be prevalent are listed below;

- At the head of a sewer system, with receiving conduits having diameters in excess of 800mm. This was confirmed by Ashley et al. (1992).
- Downstream of flow partitions (including overflows).
- In sections were the flow is under downstream influence, with sudden reductions in energy slope and ambient velocities.
- Abrupt changes on the geometry of the conduit.

- Localised obstacles, building rubble, weirs etc.
- Downstream of erodible storage zones, i.e. silt traps.

In a three year study, sediment deposition in a 480m stretch of the Marseille No. 13 trunk sewer was monitored at 10 metre intervals 3 times a week, (Laplace et al., 1990 & 1992). The main aim of this work was to investigate the special temporal changes in the sediment deposits, in terms of volume and physical properties.

At the start of the study the whole sewer length was cleaned to ensure no sediment was present. During the three years of the study a total of 120 m^3 of sediment was deposited along the invert of the sewer. In the long term, the rate of sediment deposition was found to be non-uniform, being affected, to varying degrees, by storm events. During storms at the start of the study, it was found that a substantial amount of sediment would be deposited, however, as the sediment deposits gained in volume the effects of rainfall became less important. Additionally, it was found that where material was eroded during storm conditions the volumes involved were dependent upon the antecedent dry weather period.

When sediment deposition during DWF was considered it was found that rates of build up were approximately uniform in the short term. However, the data obtained indicated that, in the long term, the volume of sediment deposit present increases asymptotically towards a maximum level, this finding being consistent with recent changes in UK design practice (Ackers et al., 1994 and Butler et al., 1995a & b) and observations made in Dundee by Ashley et al. (1992). The French researchers explain the asymptotic deposition rate as being due to changes in the ambient hydraulic conditions generated by the sediments. It was found that their presence had caused the invert gradient to gradually increase over the 3 years of the study from 1‰ to 4.5‰, which in turn generated an increase in the ambient velocity conditions, and consequently increased the sediment transport capacity. This increased transport capacity means that larger sediment particles can be transported in the flow, and this is used by the researchers to explain a gradual increase in the median particle size of the deposited sediment particles.

The researchers found that the particle size characteristics of the sediment deposits did vary from site to site with d_{50} in the range 0.5 - 5.0mm, the coarser sediments being found at the head of the system. The particle sizes are illustrated in Figure 16.

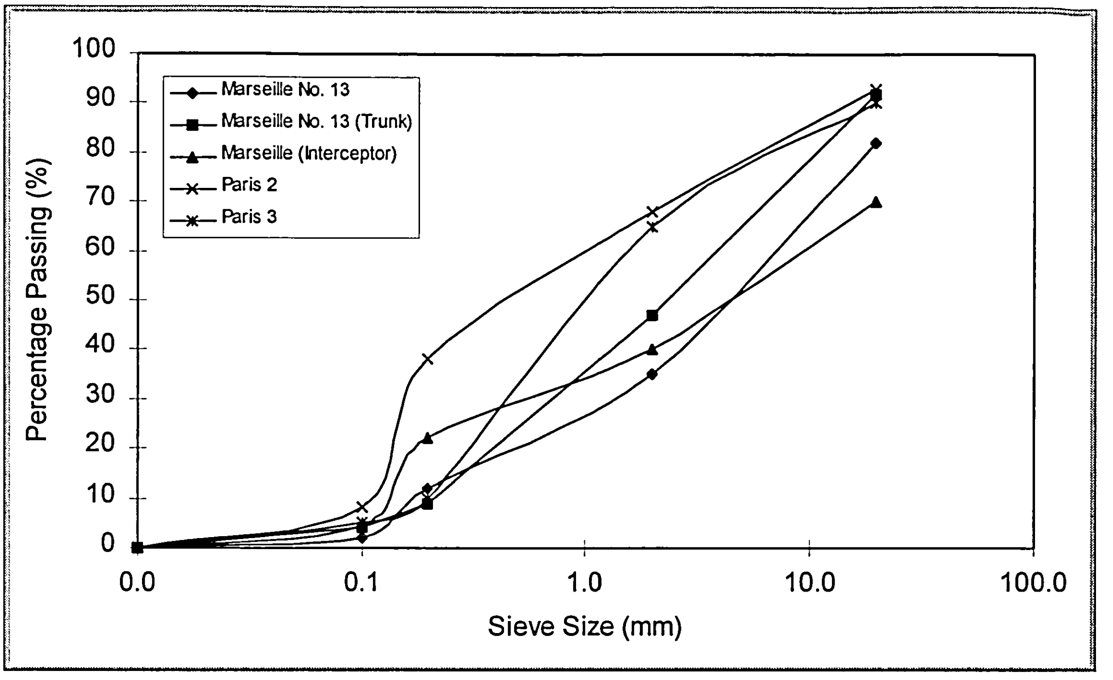

Figure 16 : French deposited bed particle size distribution
(adapted from Bachoc, 1991)

Based on the data collected detailing the nature and location of sediment deposits, a site specific relationship was generated (Laplace et al., 1992 and Bachoc et al., 1993) which could be used to estimate where sediments would deposit and their median particle size. The relationships developed took the general form shown in equation 70 and 71.

$$d_{50} = a \times RI + b \qquad \text{....70}$$

$$d_{50} = c \times \tau_o + d \qquad \text{....71}$$

Where *R* is the hydraulic radius, I is the hydraulic gradient, τ_o is the bed shear stress and *a, b, c* and *d* are site specific constants. These relationships were used as the starting point in determining where, in a system, deposition would occur. Application of the relationships suggested that during DWF for a d_{50} range of 1.00 - 1.50mm (daily trough and peak respectively) sediment would deposit in one of 3 conditions;

- Flat sections ($S_0 \leq 10‰$), where the diameter is in excess of 800mm
- At the head of systems
- In oversized sections

Additionally, it is also suggested that erosion will occur in oversized galleries (for particles ≤ 2.00mm) when rainfall exceeds intensity 5mm/h, and over the whole system when rainfall exceeds 20mm/h.

The French researchers acknowledge that the material being transported at the bed is the main source of material for deposition in sewer networks. Lin et al. (1993a & b) hypothesise that to reduce sediment deposition in sewerage systems engineers must first gain some control over the material being transported at the bed. However, Lin et al. (1993a & b) recognise that devising a method which can be used to obtain representative samples of material moving at the bed is not a straight-forward procedure.

The sample collection procedure devised consisted of open topped containers installed in an existing substantial (~0.35m) sediment deposit, based on a method developed by Hardwick and Willets (1991). To determine the optimum size of the aperture at the top of the containers the mean saltation length relationships obtained by Einstein (1950), Hayashi and Ozaki (1980) and van Rijn (1984) from tests based on inorganic materials were used, and a width of 100mm was selected.

Field trials indicated that the containers were efficient in trapping the material moving at the bed, however it is recognised that some particles may not settle due to circulation patterns generated just inside the open containers. The containers were installed at two very different points in the Marseilles N°· 13 trunk sewer;

1. At the head of the trunk sewer, where the sediment deposit was found to be coarse.
2. Near the outlet, where the ambient flow velocities are lower and the sediment deposit is finer and had a higher organic content.

Based on the data collected, Lin et al. (1993a & b) were able to determine the volumetric near bed transport rates at each of the test sites. Average bulk near bed solids transport rates were found to be 2.58 l/h (1.81 l/h dry). For site 1 rates varied from 1.15 - 29.1 l/day and 0.93 - 1.26 l/day for site 2. At the upstream site it was found that the amounts of material obtained for a given time step were mainly dependent on the time of day at which samples were obtained, and to some extent on the flowrates. However, at the downstream site, transport rates were found to be dependent upon partial erosion of the upstream mass of sediment deposit.

From the presented data it is not clear what effect the sites had on each other, i.e. the affect trapping solids at the upstream site has on downstream data collection.

Analysis of the sediment bed formation rates showed that they were approximately equal to the rate at which solids being transported at the invert entered the system, 44.20 l/day and 43.40 l/day respectively. Based on this data, Lin et al. (1993b) hypothesise that the material which enters the system as bed-load is the main source of material for deposition and to avoid this deposition the material being transported at the bed should be arrested at the inlet.

Based on observations of the long term sediment build up in the sewer Lin & Le Guennec (1995) developed a site specific methodology to predict the temporal, and spatial changes in bed depth in the sewer length considered. The basis of the relationship is the Meyer-Peter model (Meyer-Peter and Muller, 1948) as presented by Wang (1977), the relationship employed is illustrated in equation 72.

$$\frac{q_{s,i}^{*}}{\sqrt{(s-1)gd_i^3}} = 8\left(\tau_i^{*} - \tau_{c,i}^{*}\right)^{3/2} \qquad ....72$$

Where τ_i^* is the non dimensional near bed shear stress, as defined in equation 73, and $\tau_{c,i}^*$ is the non dimensional critical shear stress and is estimated using equations 74 and 75.

$$\tau_i^{*} = \frac{\tau}{\rho g(s-1)d_i} \qquad ....73$$

$$\tau_{c,i}^{*} = \frac{0.47}{1.79\left(d_i/d_{50}\right)^{0.947}} \text{ for } d_i/d_{50} < 0.4 \qquad ....74$$

$$\tau_{c,i}^{*} = \frac{0.47}{\left(d_i/d_{50}\right)^{0.314}} \text{ for } d_i/d_{50} > 0.4 \qquad ....75$$

The actual bed-load transport rate at a given point, $q_{s,i}$ is then estimated using a relationship proposed by Daubert and Lebreton (1967) which is illustrated in equation 76;

$$\frac{dq_{s,i}}{dx} = \alpha \frac{w_s}{u_*}\left(q_{s,i}^{*} - q_{s,i}\right) \qquad ....76$$

Where $q_{s,i}^*$ and $q_{s,i}$ are the non dimensional shear stress and critical non dimensional shear stress respectively. Using this relationship the prediction of the rate of deposition, or erosion can be made, i.e.;

If $q_{s,i}^* > q_{s,i}$ then erosion occurs, or

If $q_{s,i}^* < q_{s,i}$ then deposition will occur.

The near bed transport rate, may then be determined for each of the size fractions considered, and then the sub-total summed to give the transport rate per unit width, as expressed in equation 77;

$$q_{s,b} = \sum_{k=1}^{n} \Delta p_i q_{s,k} \qquad ....77$$

Lin et al. (1995) first calibrated the methodology using 200 days of data relating to the long term build-up of sediment deposits in the test section, the relationship was than validated using over 1000 days of data from the downstream site, the validation data are shown in Figure 17.

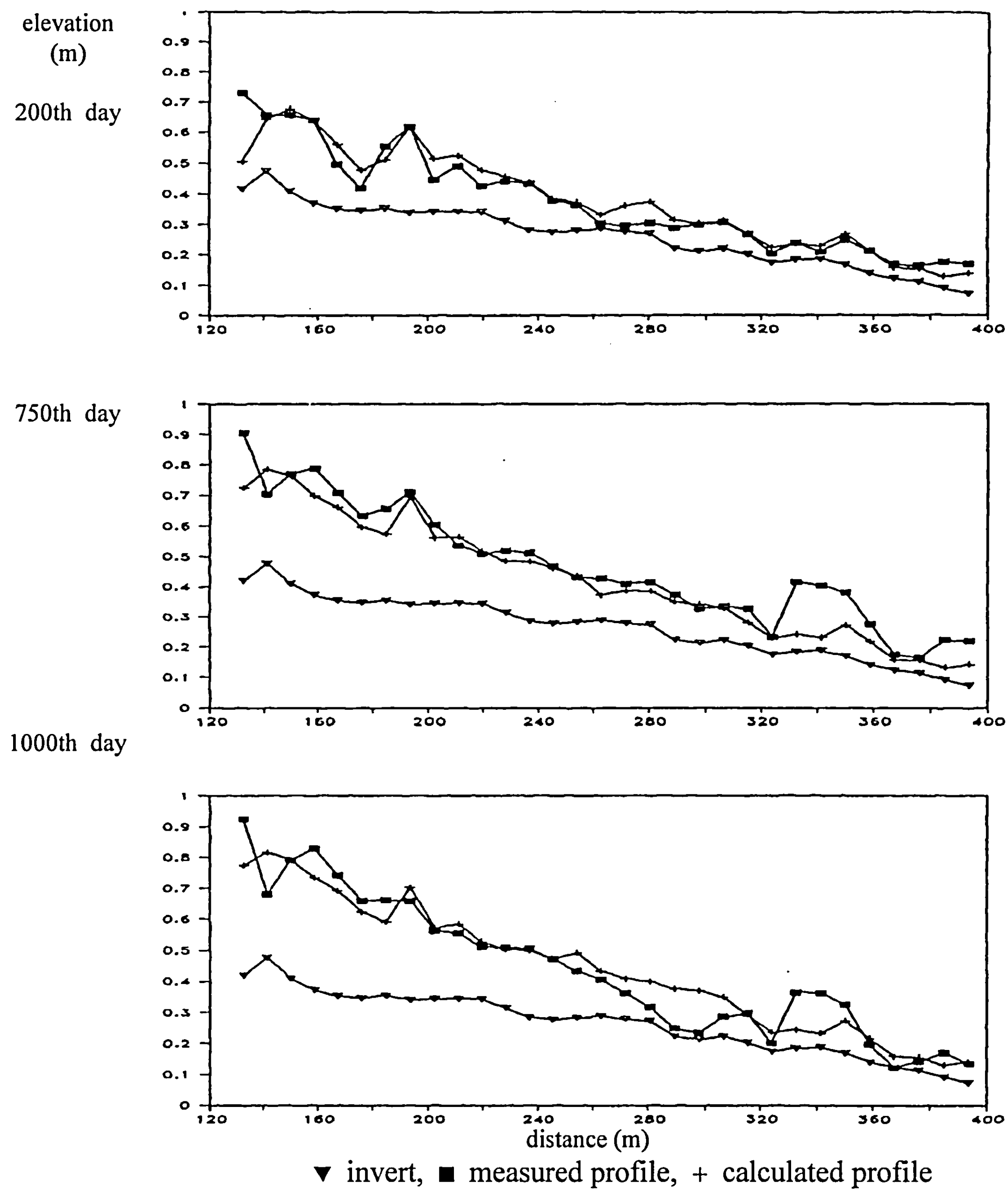

Figure 17 : Performance of the relationship obtained by Lin & Le Guennec, (1995)

Although the relationship obtained by Lin & Le Guennec (1995) does provide a good fit to the site data for the long term development of the sediment bed, little detail is given relating to the performance of the bed-load transport component of the methodology. It appears that the data collected relating to transport at the bed (Lin & Le Guennec, 1995) was only used for the validation procedure, where particle characteristics were required. Due to the lack of information concerning the near bed solids component of the methodology, the model cannot be further assessed as part of the current project.

At separate sites in France, Bertrand-Krajewski et al. (1995) carried out similar work in 1993 and 1994 to that of Lin et al. (1993a & b) with the aim of characterising solids caught in sediment traps and assessing their efficiency, and also how to alleviate septicity problems associated with silt traps.

Two separate field sites were selected in Bordeaux, the sites had the characteristics described in Table 10.

TABLE 10 : SILT TRAP FIELD SITES USED BY Bertrand-Krajewski et al. (1995) FOR DATA COLLECTION

	Site No. 1	Site No. 2
Catchment Area (ha)	6.5	503
Impervious Area (%)	47	50
Sewer Type	Combined	Combined
Invert Gradient	3‰	5‰
Silt Trap Volume (litres)	2700	57000

Each of the silt traps used had lateral extensions, in that their width is in excess of that of the sewer. Relatively small sediment traps were fitted laterally along the entry and exit to the silt trap at invert level. The remainder of the silt trap surface was then covered to prevent filling and to better assess the efficiency of the sediment traps. Data were collected in both DWF and storm conditions, however the main emphasis was on the latter.

Analysis of the rates at which the traps filled showed that the total mass of material collected in the trap during storms was correlated with the total rainfall height for depth of less than 50mm. During storm events with rainfall depths in excess of 50mm it was found that the traps totally filled. The researchers, by using linear regression, obtained the relationship shown in equation 78 (r^2=0.97);

$$M_t = 388.09 D_r \qquad \text{....78}$$

Were M_t is the total mass trapped and D_r is the total depth of rain. The data also showed that most material was collected in those traps positioned along the central axis of the sewer. These traps also collected the material with the lowest organic content. Based on the distribution of the material trapped in the containers the researchers hypothesise that extending the silt traps laterally decreases the efficiency, as it reduces the ambient velocity and causes lighter materials, which are travelling higher in the flow column, to settle as well as the inorganics moving at the bed. As it is the inorganic sands and gravels that plant operators wish to remove, the researchers recommend smaller, regularly emptied, silt traps.

Although the relationship obtained by Bertrand-Krajewski et al. (1995) fits well to the data presented, it is rather simplistic as it does not take into account any affect of the antecedent dry weather period (ADWP). Laplace at al. (1992) found that ADWP controlled the amount eroded from a sediment bed.

3.4 Discussion

The literature reviewed in this chapter has illustrated the problems associated with the presence of sediment in sewerage systems, both in the U.K. and elsewhere. The problems are principally perceived as hydraulic in nature, however greater importance is now being placed on the pollutant potential of sediment in transport, and that deposited. Considerable variations have been highlighted in the nature of sediment deposits in different sewers, catchments, and countries. Although much of the variation in sediment characteristics can be attributed to site specific characteristics (catchment detail, sewer maintenance strategies etc.), some emphasis must also be placed on differences in data collection methodologies and sample testing protocols.

Only a limited amount of work has been undertaken investigating near bed solids transport in sewers. Where the data collection is reliable, much of the data available gives only inferential details of material characteristics. From the data available it can be seen that there is considerable variation in the material collected at different sites, even when in the same sewer length. This is undoubtedly due to ambient conditions and material supply conditions.

Additionally, only inferential data are available which detail variations in the material in transport throughout the DWF pattern. The importance of the material in transport at the bed has been shown when considering sources of material for deposition and the pollution impact of storms.

The work which is, perhaps, of greatest importance to this study, in terms of data collection, is the work of Lin (1988), Lin et al. (1993a and b) and Lin & Le Guennec (1995). As this work reports fieldwork relating to the collection of "bed-load" in a trunk sewer, and gives data with which that collected as part of the current project may be compared.

The work of Verbanck (1995a), regarding near bed solids transport, is of lesser importance as the data collection on which much of the analysis is based is subjective. To remedy this the method employed to collected samples used by Verbanck (1995a) will be assessed as part of this project.

Of the research undertaken in the Dundee sewer system the work of Coghlan (1995) is perhaps of greatest importance, as the work reported has investigated the transport of solids in DWF and storm conditions in the sewer to be studied in the current project. Coghlan (1994) highlighted parameters which were found to influence sediment transport in the Dundee interceptor sewer. Additionally the short-lived study undertaken investigating near bed solids transport acted as a prototype study for the current project, in terms of data collection methods and sample testing.

The work of Wotherspoon (1994) has less direct importance to this study, although it does give an indication of the extent of sediment erosion in the interceptor sewer during storm conditions, although any impact the eroded material has on any first flush observed cannot be confirmed.

Chapter 4 : Laboratory Based Sewer Sediment Transport Studies

This chapter seeks to bring together much of relevant contemporary sewer sediments research undertaken in a laboratory environment.

The current project was undertaken in collaboration with the Universities of Newcastle and Sheffield. The aim of the work undertaken in Sheffield was to investigate the erosion of sewer sediments, and attempt to link them to first foul flush in a laboratory environment. Because of the collaboration with Sheffield, the work of Skipworth (Ashley et al, 1995, Skipworth et al., 1995 and Skipworth, 1996) is given emphasis here.

The work of Torfs (1995) is also emphasised as it provides a valuable link between alluvial and sewer sediment research.

In recent years there has been a great deal of work undertaken investigating sediment transport in sewers, and this has recently culminated in the proposals for a new sewer design methodology and a reassessment of the term "self cleansing sewer". The main centres of research, in the U.K. have been H.R. Wallingford, University of Newcastle and more recently the University of Sheffield. This section will deal with the work undertaken in these research establishments, and others, and will discuss the main advances in the laboratory. As laboratory based sewers sediments research, when collated together, is somewhat repetitive the reporting in sections 4.3 "Transport at the Limit of Deposition in Pipes" and 4.4 "Transport Over a Deposited Bed" have been restricted to brief descriptions of the test aims, sediment characteristics and principal results.

4.1 Collaborative Sewer Sediments Research Undertaken at the University of Sheffield

In collaboration with work undertaken in Dundee and Newcastle (Ashley et al., 1995) a series of sediment transport experiments were undertaken in the University of Sheffield (Ashley et al., 1995, Skipworth et al.,1995 and Skipworth, 1996. The principal aim of the work undertaken in Sheffield was to investigate, under laboratory conditions, the erosion and transport of cohesive-*like* sediment deposits, analogous to those found in some combined sewer systems.

Crushed olivestone (100 mesh) was used throughout the erosion tests as a surrogate sediment. This sediment was shown (Alvarez, 1992) to exhibit properties that were analogous to typical class C (Crabtree, 1988) sewer sediment. Rheological measurements, using the crushed olive stone, were undertaken in Dundee and a relationship between moisture content and yield strength for the sediment was established, based on the work of Wotherspoon (1994).

A range of flow hydrographs were used to erode the sediment beds in the study, each of which comprised of a rising limb, with a linear increase in flowrate with respect to time, followed by a steady flowrate of magnitude equal to that of the peak value of the rising limb. The rate of increase in flow and influence of pipe slope were also investigated. Two types of tests were undertaken, termed primary and secondary. Primary tests were carried out on previously undisturbed beds whilst secondary tests were performed on the resultant bed at the end of a primary test i.e. a previously partially eroded bed. The results of the primary tests showed that the cohesive-*like* sediment beds were more resilient as the depth of erosion increased and that a constant yield strength was attained beyond a certain depth of erosion (Ashley et al., 1995). Typical pollutographs are shown in Figure 18.

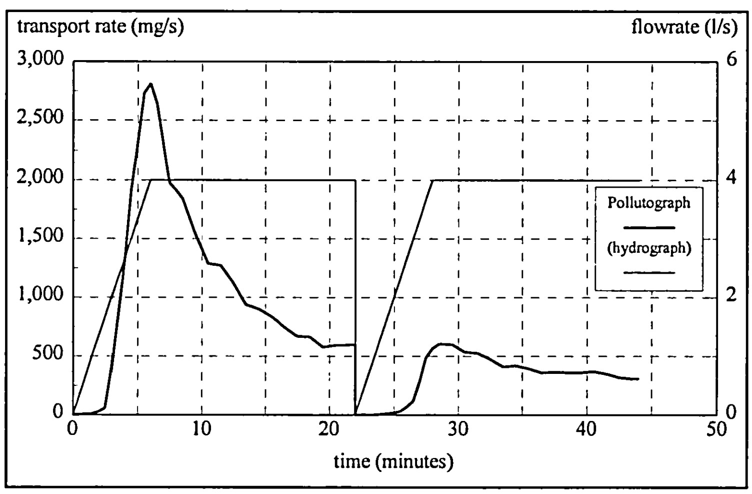

Figure 18 : Typical example of primary and secondary pollutographs with the same inflow hydrograph (from Ashley et al., 1995)

Skipworth (1996) observed that an increase in the duration of the rising limb of the hydrograph resulted in a suppression of the peak transport rate in tests using similar starting conditions, this be due to the slower rate of shear stress application. This effect was greatest in the tests performed at the steeper slope of 1/500 and these results are consistent with the theory that a cohesive-*like* sediment bed exists as a weaker layer of sediment of increasing strength with depth, overlying a layer of uniform strength. Collectively, the primary tests indicated the existence of a critical ultimate bed shear stress. Above this value the steady transport rate was insensitive to a change in the applied bed shear stress, whilst below this value the transport rate reduced with the reduction in bed shear stress (Skipworth, 1996).

Skipworth (1996) defines the first flush phenomena, as observed in the laboratory as:

"The proportion of the test before a steady transport rate is reached"

This corresponds with 0 to 20 minutes for the primary hydrograph in the figure above.

Skipworth (1996) found that:

1. The duration of the first flush was a function of the flow acceleration during the rising limb of the hydrograph and of the ultimate bed shear stress.
2. The mass of sediment contained in the first flush was independent of these variables but dependent on pipe slope, although no conclusions are given regarding this.
3. The mass of sediment contained in the first flush increased with an increase in pipe slope.
4. The first flush corresponded to the erosion of an overlying weaker layer of the surrogate sediment.

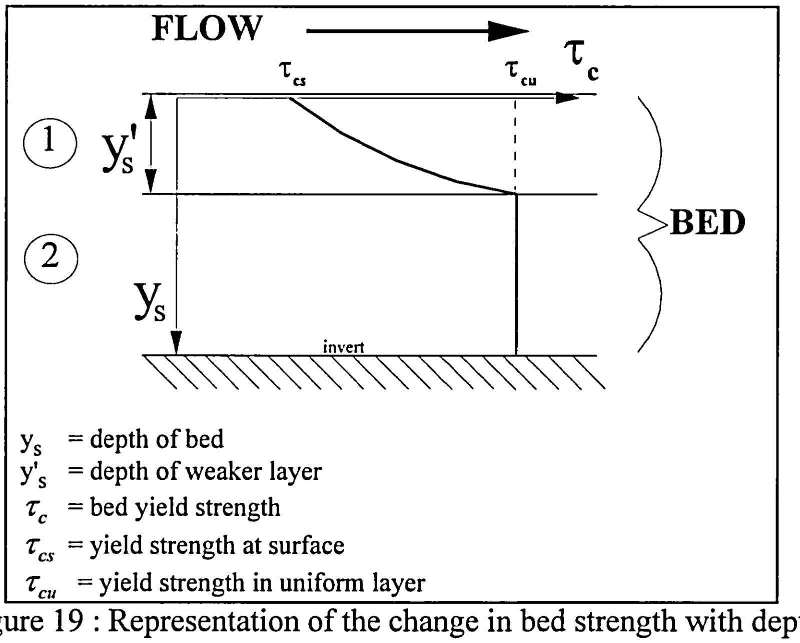

Figure 19 : Representation of the change in bed strength with depth (Ashley et al, 1995)

Figure 19 shows how Skipworth modelled the bed as a weaker layer of sediment, in which the strength increased with depth, overlying a layer of uniform strength (Ashley et al., 1995). Skipworth found that the structure of the bed appeared to be different for different pipe slopes with an increased strength of bed at higher slopes but with a deeper variable strength layer. The bed strength was considered therefore to be related to the density, and hence the moisture content of the bed, (Wotherspoon, 1994, Torfs, 1995) which in turn dictates the dispersion of the particles that make up the bed. A conceptual erosion model based on the perceived physical processes was developed to simulate the movement of cohesive-*like* sediments in combined sewers under time varying flow conditions. Skipworth (1996) hypothesises that the model highlights the importance of the rheological properties of the sediment and explained the occurrence of the first flush in sewers. The model was based on a transport rate equation proposed by Parchure and Mehta (1985) for the erosion of uniform soft cohesive sediment deposits in estuaries and can be applied to any in-pipe cohesive-*like* sediment bed provided that the bed strength variation with respect to depth can be estimated accurately (Skipworth,1996). The model proposed by is illustrated in equation 79.

$$T = M\left\{\frac{\tau_a - \tau_c}{\tau_c}\right\} \qquad \text{....79}$$

Where τ_a = applied bed shear stress, τ_c = bed strength, T = transport rate, M = transport rate when $\tau_a = 2\tau_c$. Values of τ_{cs}, τ_{cu}, M and d' were estimated from experimental data. Typical comparisons of the experimental and predicted results are given in Figure 20 (primary tests) and 21 (secondary tests).

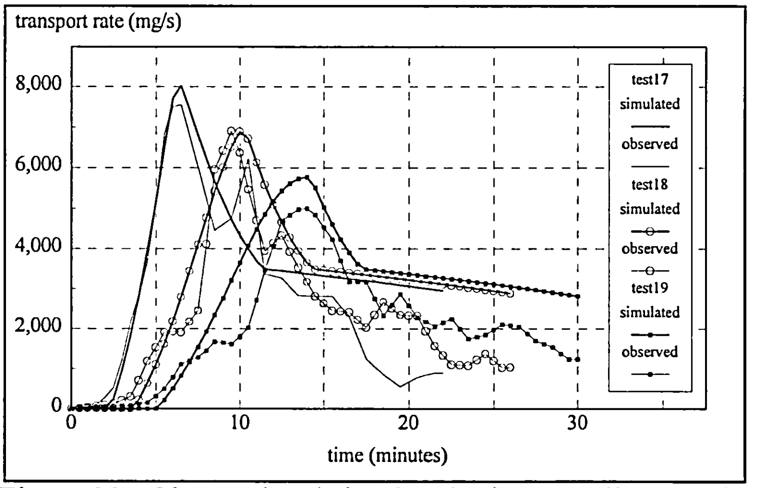

Figure 20 : Observed and simulated primary pollutographs
(s=1/500 & Q=4l/s, from Ashley et al., 1995)

Although the relationship obtained by Skipworth (Ashley et al, 1995, Skipworth et al., 1995 and Skipworth 1996) provides a good fit with the data collected as part of the laboratory work undertaken at the University of Sheffield, it is difficult to envisage how it could be applied to sediment movement in a 'real' combined sewer. This is principally due to the shape of the hydrograph employed in the laboratory, and the method used to establish a sediment bed. This was due to the bed being placed when there was no flow in the pipe and the input hydrograph used started at a velocity of zero, under such circumstances some degree of erosion would be inevitable. A hydrograph which began with steady flow, before a gradual increase in flow would have been more representative. The initial hydrograph employed by Skipworth (Ashley et al., 1995) represents more typically those observed in storm sewers, where the sediments are not normally cohesive.

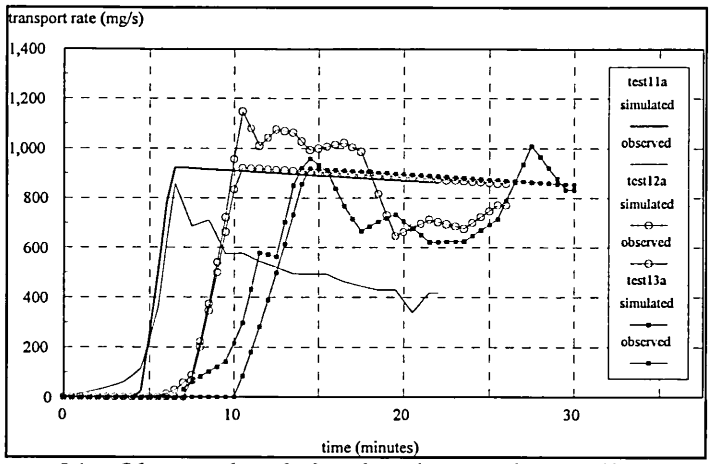

Figure 21 : Observed and simulated secondary pollutographs
(s=1/1000 & Q=41/S, from Ashley et al., 1995)

In similar tests, investigating mud/sand mixtures, Torfs (1995) allowed laboratory sediment to consolidate in the flume under water. Additionally, Torfs made a concerted effort to avoid erosion of the upper levels of the test sediment, other than loose material resting on the surface, before gradually increasing the bed shear levels until erosion was initiated.

4.2 Torfs (1995)

The work of Torfs (1995), although primarily concerned with estuarine sediment erosion, is perhaps more relevant to sewer sediment research than that of Skipworth (Ashley et al., 1995). Torfs (1995) investigated uniform and stratified mud/sand mixtures with the aim of examining the transition between cohesive and non-cohesive sediments. The sediments tested were in the density range 1010 kg/m^3 to 1650 kg/m^3, and were composed of a range of inorganic particle sizes and material types. The use of sand and clay mixtures represents more accurately the sediments experienced in some combined sewers, and the Dundee interceptor in particular (Wotherspoon, 1994). Torfs (1995) found that the critical shear stress of a sediment was dependent on the percentage of fines (<63μm) in the deposit, which were studied using the Atterberg limit tests (Smith, 1990). Additionally it was observed that the bed-load transport rate was directly related to the bed shear levels.

The main result of the tests and analysis undertaken by Torfs (1995) is the proposal of a methodology for the prediction of sediment (cohesive and non-cohesive) erosion. Where sediments are cohesive, equation 80 is used to estimate the erosion rate, E, ($kgs^{-1}m^{-2}$), where E_m and α are constants:

$$E = E_m\left(\frac{\tau_b - \tau_c}{\tau_c}\right)^{\alpha} \qquad ....80$$

The relationship above is similar to the excess shear relationship proposed by Skipworth (1995), as discussed in section 4.1 "Collaborative Work in Sewer Sediments Research Undertaken at the University of Sheffield". Where the sediment bed is not cohesive, existing empirical relationships are recommended by Torfs (1995).

The work of Torfs is important to sewer sediment research as it acknowledges the presence of stratified cohesive sediments of varying density, as experienced in sewer systems. Additionally the particle characteristics are much more relevant to those observed in the field than those employed by other laboratory based research programmes (e.g. Skipworth, 1995, May, 1994, Ab Ghani 1993 etc.). The work of Torfs (1995) does have two primary limitations; the use of a rectangular flume for tests and the use of stepped hydrographs. The use of stepped hydrographs means that the resultant force impulse may prematurely overcome, at least temporarily, the inertia of the deposited sediment.

4.3 Transport at Limit of Deposition in Pipes

In many sewer conduits the hydraulic channels are such that no permanent sediment bed can form, other than occasional intermittent solids. This transport condition is described, in laboratory studies, as being at the limit at deposition, and can be defined (Ackers et al., 1994) more precisely as;

> **"the velocity at which flow conditions are just sufficient to transport a given concentration of sediment without formation of a stationary deposit"**

Over the past twenty years a substantial amount of laboratory work has been undertaken investigating sediment transport at the limit of deposition condition, both in the UK and elsewhere. The main, recent, progress in this field has been made by the researchers listed below;

- Novak and Nalluri (1975)
- Macke (1982)
- May et al (1989)
- May (1993)
- Mayerle, Nalluri and Novak (1991)
- Nalluri and Ab. Ghani (1993)
- Ab. Ghani (1993)

- Nalluri, Ab. Ghani and El-Zaemey (1994)
- May (1994)

It should be noted that in these laboratory studies the term bed-load refers to the maximum possible transport rate of material along the bed of a pipe, or channel, without the tendency for the material to deposit. The material used for testing predominately consists of a single sized, or uniformly graded, cohesionless sediment of high (2.53 < S.G. <2.65) specific gravity. Therefore this material is very different from the occasionally highly organic heterogeneous material moving at the bed in some sewers.

Novak and Nalluri (1975)

Novak and Nalluri (1975) recognised that an extensive amount of laboratory based research had been undertaken investigating suspended sediment transport (but usually at much higher concentrations than are experienced in the field), and considerably less attention had been paid to the transport of sediment as 'bed-load' in pipes and channels. The work carried out by these researchers, in circular channels, utilised 152mm and 305mm PVC pipes, 10m and 8m long respectively. The material used as a sediment took the form of uniformly graded dry sands ranging from 0.15mm to 2.00mm. Sediment concentrations, C_v, were in the range 1.7 - 117ppm and 66 - 2400ppm for the 305mm and 152mm channels respectively.

Analysis of the results obtained generated equation 81 which can be applied to both circular and rectangular channels.

$$C_v = 4.10\lambda_c^{2.04}\left(\frac{d}{R}\right)^{-0.538}\left(\frac{V_L^2}{8g(s-1)R}\right)^{1.54} \qquad ....81$$

The term V_L is the 'limiting flow velocity without deposition', and is common to most bed-load transport relationships. V_L is, hence, the flow velocity at which a given particle will just move, as bed-load, and not deposit. Clearly this parameter can be relatively easily defined in laboratory conditions, using materials of uniform characteristics. However, defining such a parameter in a sewer, where both the sediment being transported and the physical and hydraulic boundary conditions are continually changing, requires a degree of judgement.

Macke 1982

With the aim of establishing a framework to maintain sewers in a sediment free condition Macke (1982) augmented existing classical laboratory data with new laboratory studies and site observations to obtain sediment transport equations. The laboratory work was undertaken in pipes, flowing full or half full, with internal diameters of 192mm, 290mm and 445mm transporting sands with a d_{50} of 0.16mm - 0.37mm at transport rates of 10^{-6} - 4×10^{-3} $Nm^{1.5}s^{-2.5}$.

In developing a transport model, Macke (1982) hypothesised that the energy expended in overcoming frictional resistance by the flow is converted into turbulent fluctuations which maintain the sediment in motion and/or suspension. The results of his theoretical analysis are then related to laboratory data collection using the general relationship below in equation 82.

$$Q_{s*} = Q_s \rho g(s-1)w_s^{1.5} \qquad ....82$$

Where w_s, the particle settling velocity, is determined using equation 83;

$$w_s = \frac{\sqrt{\left(9\nu^2 + d^2 g(s-1)(0.03869 + 0.0248d)\times10^{-9}\right)} - 3\nu}{(0.11607 + 0.074405d)\times10^{-3}} \qquad ....83$$

Macke (1982) divided sediment transport into two distinct regions. In *Region I* sediment transport takes the form of a heterogeneous flow condition where sediments are maintained mainly in the suspended mode of transport. In *Region II* solids are transported predominately as bed-load, with a limited amount of deposition. For the Region I condition a relationship was obtained in the form of equation 84 (also illustrated in Figure 22).

$$Q_{s*} = Q_s \rho g(s-1)w_s^{1.5} = 1.64\times10^{-4}\tau_o^3 \qquad ....84$$

This relationship was then plotted along with data from several classical studies, notably Durand (1953), Einstein (1955) and Robinson & Graf (1972), on a logarithmic plot. Despite the fact that much of the additional data were well outside the range of data collected, as shown in Table 11, a good fit was generally obtained.

TABLE 11 : SCOPE OF ADDITIONAL DATA USED BY Macke (1982)

Parameter	Low	High
Pipe Diameter	0.05m	2.4m
Sediment Concentration	1×10^{-7} ppm	2×10^{-5} ppm
Solids Transport Rate	1×10^{-6} $N^{1.5}ms^{-2.5}$	$3.7\times10^{-6}N^{1.5}ms^{-2.5}$
Particle Size	0.1mm	3.0mm
Shear Stress	5×10^{-1} Nm^{-2}	7.4×10^{1} Nm^{-2}

Despite the success with the suspended mode of sediment transport, Region I, it was not possible to obtain a single relationship for the bed-load mode. Instead a series of individual relationships were obtained, one for each of the data sets analysed. Which suggests that the work of Macke may have overlooked a factor where the transport of material as bed-load is concerned.

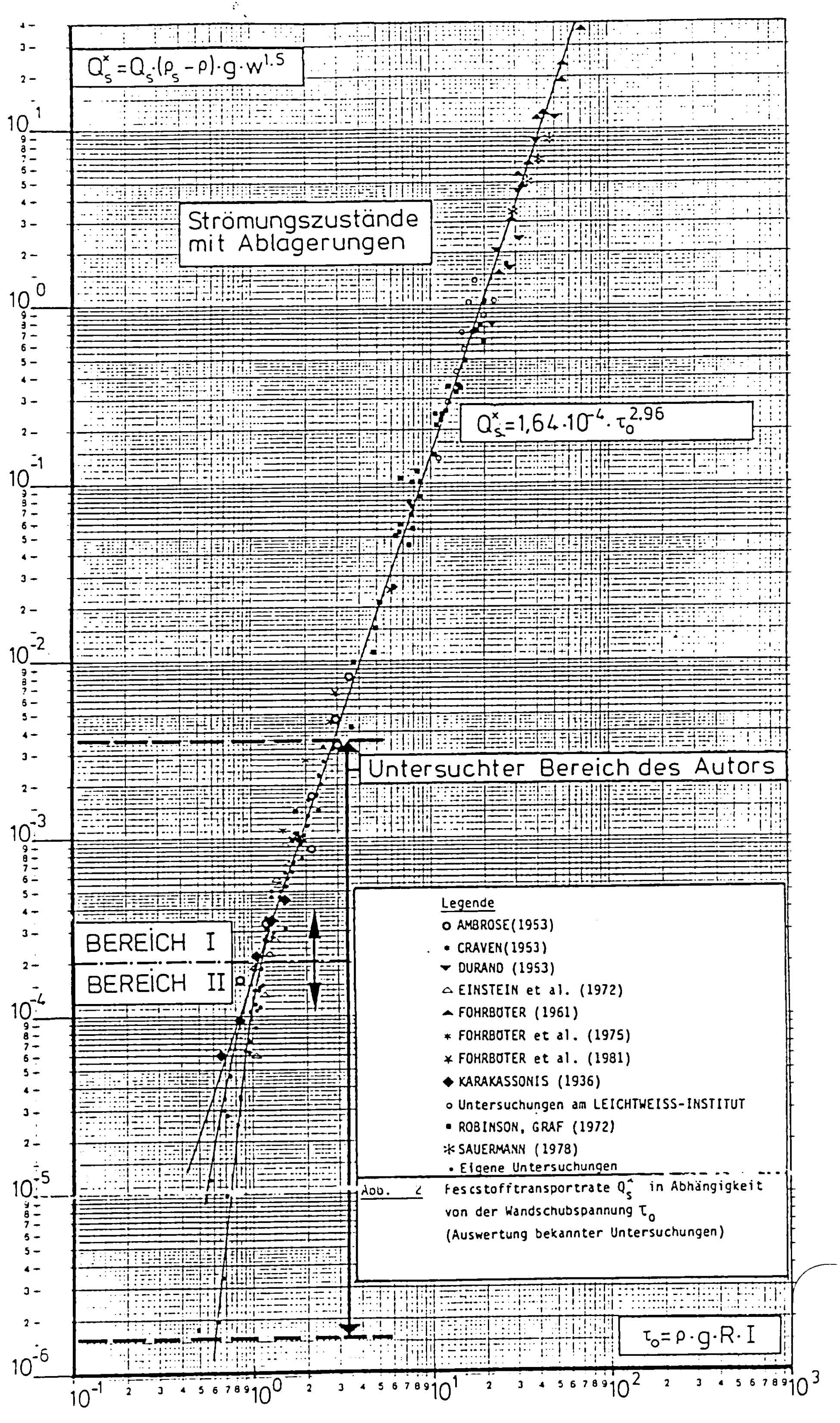

Figure 22 : Relationship obtained by Macke (1982)

Ackers et al., (1994) suggest that the division between Region I and Region II should be made based on settling velocity criteria, in relation to bed shear velocity, i.e. if criteria set in equation 85 are met then the material will travel in suspension, otherwise transport will be as bed-load.

$$\frac{u_*}{w_s} > 0.75 \qquad \text{....85}$$

Where the shear velocity u_* is calculated using equation 86.

$$u_* = V\sqrt{\frac{\lambda_c}{8}} \qquad \text{....86}$$

Mayerle, Nalluri and Novak (1991)

Based on a number of experiments dealing with bed-load transport of non-cohesive sediments in fixed bed conduits, Mayerle et al (1991) obtained 2 relationships which deal with transport in circular pipes. The first equation does not take into account the affect of the friction factor of the pipe, whilst the second does. These relationships are illustrated in equations 87 and 88 respectively;

$$C_v = 1.73\times10^{-3}\left(\frac{d}{R}\right)^{0.783}\left(\frac{V_L^2}{g(s-1)R}\right)^{2.17} \qquad \text{....87}$$

The second formula takes into account the increase in friction caused be the presence of sediment;

$$C_v = 3.63\times10^{-3}\left(\frac{d}{R}\right)^{0.333}\left(\frac{D_{gr}^{0.778}}{\lambda_c}\right)\left(\frac{V_L^2}{g(s-1)R}\right)^{2.78} \qquad \text{....88}$$

Where D_{gr}, the dimensionless grain size, is defined using equation 89;

$$D_{gr} = \left(\frac{g(s-1)}{v^2}\right)^{1/3} d \qquad \text{....89}$$

Mayerle et al (1991), determined the composite friction factor, λ_c using the Colebrook-White equation and the equivalent roughness k_c, as illustrated in equation 90;

$$\frac{k_c - k_o}{R} = 0.0130 D_{gr}^{0.24} C_v^{0.40} \qquad \text{....90}$$

The experimental work carried out by Mayerle et al (1991) was conducted in two rectangular flumes, with smooth and rough beds, and in a 152mm diameter 20m long tilting pipe channel with a smooth bed. Graded sands and gravels of d_{50} ranging from 0.5mm to 8.74mm with a density of 2550kg/m^3 were used as a sediment.

May (1993), in a review of the work of Mayerle et al (1991) found that the data and equations generated were, on the whole, in general agreement with HR Wallingford data obtained with smooth pipes and in a 299mm diameter concrete conduit.

Nalluri and Ab. Ghani (1993)

Nalluri and Ab. Ghani (1993), in a study investigating sediment transport at the limit of deposition in smooth and rough pipe sections obtained a sediment transport relationship. Using the data generated, along with existing data, a review of existing design practice was undertaken.

Data were collected from three tilting bed channels of 154mm, 305mm and 450mm diameter and 20.5m in length. Graded sands and gravels were used as sediment, with d_{50} in the rage 0.5mm to 8.3mm. The average density of the sediments used was 2550kg/m^3. Flow depths in the study varied from 15% - 80% of the pipe diameter. Based on this work Nalluri and Ab. Ghani (1993) obtained the relationship illustrated in equation 91;

$$C_v = 4.52 \times 10^{-3} \left(\frac{d_{50}}{R} \right)^{0.045} D_{gr}^{0.545} \lambda_c^{1.18} \left(\frac{V_L^2}{g(s-1)R} \right)^{2.27} \qquad ....91$$

The equation above assumes that a sediment is present, if this is not the case the composite friction factor, λ_c, should then be replaced with the clean pipe friction factor, λ_o, using equation 92;

$$\lambda_c = 1.20 \lambda_o C_v^{0.02} D_{gr}^{0.01} \qquad ....92$$

The equation for transport with sediment is then modified to that shown in equation 93;

$$C_v = 4.94 \times 10^{-3} \left(\frac{d_{50}}{R} \right)^{0.046} D_{gr}^{0.570} \lambda_c^{1.21} \left(\frac{V_L^2}{g(s-1)R} \right)^{2.32} \qquad ....93$$

May (1993)

As part of the water research programme funded by the UK Department of the Environment, May (1993) carried out a series of experiments in a 21m long 450mm diameter concrete pipe. Four different gradings of sand were used with d_{50} sizes of 0.47mm, 0.58mm, 0.61mm and 0.73mm. The tests were undertaken with velocities in the range 0.4m/s - 1.3m/s.with proportional depths of 0.5, 0.75 and 1.0. The main aim of this work was to investigate flow conditions in pipes with significant levels of sediment. The average bed depth y_s varied from 13% to 27% of the pipe diameter. The study also included tests at the limit of deposition.

The model obtained by May (1993) can be applied to bed-load transport at the limit of deposition with or without a deposited bed. This relationship takes the form of that shown in equation 94.

$$C_v = \Omega \frac{D^2}{A}\left(\frac{y}{D}\right)^{0.6}\left(\frac{\lambda_g V_L^2}{8gf(s-1)D}\right)^{1.5} \qquad \text{....94}$$

Where Ω is obtained via equation 95 and Table 12;

$$G_s = \left(\frac{y}{D}\right)^{0.2}\left(\frac{\lambda_g V_L^2}{8gf(s-1)d_{50}}\right)^{0.5} \qquad \text{....95}$$

TABLE 12 : SELECTION OF Ω (May, 1993)

$G_S \leq 0.15$	$\Omega = 0$
$0.15 < G_S \leq 0.55$	$\Omega = 8.25G_S - 1.24$
$0.15 < G_S \leq 0.55$	$\Omega = 1.78G_S - 2.32$

For smooth pipes $f = 1$ and for rough $f = 2$.

Observations in laboratory flumes (May et al., 1989 Ab Ghani, 1993 and May, 1993) indicated that where the depth was below 5% of the pipe diameter the bed formed was not continuous, a condition which would affect sediment transport at the bed. To deal with this situation researchers (May et al., 1989 and Ab Ghani, 1993) have determined the total volume of sediment in the pipe length and assumed an even distribution. May (1993) however developed a methodology which involves the calculation of flow resistance and the sediment transport rate based on average characteristics of individual dunes using equations 96 and 97.

$$A_d = \frac{Z}{P_d L} \qquad \text{....96}$$

$$C_v = P_d C_{vd} \qquad \text{....97}$$

Where :
- A_d = Cross Section of Dune
- Z = Volume of Deposited Sediment
- P_d = Proportion of Pipe With Sediment
- L = Length of Pipe
- C_v = Volumetric Sediment Transport Concentration
- C_{vd} = Volumetric Transport Concentration Over Dunes

Nalluri, Ab. Ghani and El-Zaemey (1994)

Nalluri et al (1994) reported on experimental work carried out in a 305mm diameter pipe section with a fixed bed, both rough and smooth. The depth of the fixed bed was varied between 47mm, 77mm and 120mm (15%, 25% and 40% respectively) and had a varying pipe gradient of up to 1:200 (5‰). Initially smooth bed tests were undertaken, but later the bed was roughed by uniformly applying a coating of single sized sands, 0.53mm and 1.0mm. The materials used as a sediment were in the size range 0.53mm - 8.4mm. Using the data obtained, Nalluri et al (1994) obtained the relationship illustrated in equation 98.

$$\frac{V_L}{\sqrt{g(s-1)d_{50}}} = 2.56C_v^{0.165}\left(\frac{y}{D}\right)^{0.400}\left(\frac{d_{50}}{D}\right)^{-0.57}\lambda_b^{0.10} \qquad ....98$$

Where λ_b is the friction factor applying to the part of the pipe diameter covered by sediment and can be determined using equations 99 and 100.

$$\lambda_b = 6.6\lambda_c^{1.45} \qquad ....99$$

$$\lambda_c = 0.88C_v^{0.01}\left(\frac{0.5D}{y}\right)^{0.03}\lambda_o^{0.94} \qquad ....100$$

Based on this the original relationship can be expressed (Ackers, 1994) in terms of a clean pipe friction factor, as shown in equation 101;

$$C_v = 1.29\times10^{-3}\left(\frac{y_o}{D}\right)^{0.627}\left(\frac{d_{50}}{D}\right)^{0.421}\lambda_o^{-0.819}\left(\frac{V_L^2}{g(s-1)y_o}\right)^3 \qquad ....101$$

The transport relationships obtained by Nalluri et al (1994), used the observation of Mayerle (1989) that the material moving as bed-load is restricted to the centre of the pipe, typically in the width band equal to 0.5D.

The researchers tested the validity of the relationships obtained by applying them to the data obtained by Ab. Ghani (1993), May (1989) and Loveless (1991). The validation procedure indicated that the assumption of using an effective bed width of 0.5D was valid, as there was found to be good correlation between predicted and measured transport rates.

Ab. Ghani (1993)

In an extension of the work reported by Nalluri et al (1994) and Nalluri & Ab. Ghani (1993), Ab. Ghani (1993) carried out additional tests using cohesionless sediments at the limit of deposition. These tests were undertaken in 154mm diameter PVC-U pipes and in 450mm concrete pipes (jointed at 2.52m intervals) at University of Newcastle and HR Wallingford respectively. The PVC-U pipes had a maximum bed gradient of 1:167 (6‰) whilst the concrete test rig could be set at up to 1:100 (10‰).

Based on the laboratory data collected at the limit of deposition Ab. Ghani (1993) obtained a relationship, via multiple regression analysis, which is illustrated in equation 102. This relationship is in the same general form as obtained in earlier studies (Nalluri & Ab. Ghani, 1993).

$$C_v = 4.79 \times 10^{-3}\left(\frac{d_{50}}{R}\right)^{0.146} D_{gr}^{0.448}\lambda_o^{1.00}\left(\frac{V_L^2}{g(s-1)R}\right)^{2.43} \qquad ....102$$

This equation is valid for both rough and smooth pipes as, the researcher found, the pipe roughness has little affect on the sediment transport capacity.

May (1994)

May (1994) in an evaluation of relationships predicting sediment transport at the limit of deposition, further analysed data collected, and the relationships obtained, in studies which had a good experimental backing, namely;

1. Macke (1982)
2. May, Brown, Hare and Jones (1989)
3. May (1993)
4. Mayerle, Nalluri and Novak (1991)
5. Nalluri and Ab. Ghani (1993)
6. Nalluri, Ab. Ghani and El-Zaemey (1994)
7. Ab. Ghani (1993)

May (1994) recognised that most of the relationships obtained continue to predict some sediment movement, even of large particles, down to zero average flow velocity ($V_t \rightarrow 0$ ms^{-1}). Based on this the researcher employed an approach used by Novak and Nalluri (1975) which added the concept of threshold velocity to the analysis. The relationship used to predict threshold velocity in illustrated in equation 103.

$$V_t = 0.125\sqrt{g(s-1)d}\left(\frac{y}{d}\right)^{0.47} \qquad ....103$$

This equation indicates that the threshold velocity is mainly dependent on flow depth and particle size.

TABLE 13 : VALIDATION DATA USED BY Ackers et al. (1994)

Researcher	Pipe Ø (mm)	k_o (mm)	Sediment d_{50} (μm)	Specific Gravity	y/d	Flow Velocity (m/s)	C_v	No. of Tests
Macke (1982)	192, 290, 445	smooth (~0.003)	160, 370	2.63	0.20 - 0.90	0.44 - 1.21	3.7 - 1700	60
May (1982)	77, 158	smooth (~0.003)	570 - 7900	2.65	0.37 - 1.00	0.45 - 1.19	6.3 - 2110	57
May et al (1989)	299	0.15	720	2.62	0.49 - 1.00	0.50 - 1.22	0.3 - 440	48
May (1993) & Ab. Ghani (1993)	450	0.14	730	2.63	0.49 - 0.75	0.24 - 0.86	1.6 - 38	27
Ab. Ghani (1993)	154	smooth (~0.003)	930 - 9300	2.54 - 2.59	0.16 - 0.76	0.24 - 0.86	38 - 1450	39
Ab. Ghani (1993)	305	0.53	970 - 8300	2.53 - 2.58	0.18 - 0.77	0.41 - 1.00	1 - 920	71
Ab. Ghani (1993)	305	1.34	2000 - 8300	2.53 - 2.57	0.24 - 0.71	0.24 - 0.71	6.7 - 403	30

The data base of existing data (summarised in Table 13) were re-worked using multiple regression analysis and equation 104 resulted;

$$C_v = 3.03 \times 10^{-2} \left(\frac{D^2}{A} \right) \left(\frac{d}{D} \right)^{0.6} \left(1 - \frac{V_t}{V} \right)^4 \left(\frac{V^2}{g(s-1)D} \right)^{1.5} \qquad ....104$$

This relationship is valid for both rough and smooth pipes, based on the findings of Ab. Ghani (1993) who found that the pipe roughness has little influence on the sediment transport capacity at the limit of deposition.

4.4. Transport Over a Sediment Bed

In the UK, and internationally, new sewers are normally designed to be self cleansing by specification of a minimum gradient, flow velocities or bed shear levels to prevent the formation of any permanent sediment deposits. Additionally in older systems where changes to the pipe sizes or gradients cannot be accommodated (essentially older systems in city centres) self cleansing conditions may be obtained by the addition of control structures. Despite these considerations, however, a substantial amount of sewer systems are affected by sediment deposits, a recent UK study (CIRIA, 1986) estimated that approximately 25000km of sewers were affected by sediment deposition to some extent.

Based on these considerations a considerable amount of laboratory work has been undertaken in an attempt to obtain a methodology which may be used to estimate sediment transport over a deposited bed in sewers. As with the work undertaken at the limit of deposition in laboratory conditions, relationships obtained are based largely on the transport of cohesionless sediment of limited particle size distribution and high specific gravity (2.62 - 2.65) transported by a flow approaching its transport capacity.

The review undertaken herein of the work in this field will concentrate on that which is directly applicable to sewers and will essentially avoid the, largely theoretical, early work undertaken investigating sediment transport in the fluvial field.

The main progress in the field of sediment transport over sediment bed has been made by;

- Graf and Acaroglu (1968)
- Perrusquía (1991 & 1992)
- Kleijwegt (1992)
- May (1993)

- Nalluri and Alvarez (1992)
- Ackers (1984)
- Ackers (1991)
- Ab Ghani (1993)
- May (1994)
- Perrusquía & Nalluri (1995)

Graf and Acaroglu (1968)

With the aim of establishing a model which could be used to predict the total transport of solids in a conveyance system (open channels, rivers and closed conduits) Graf and Acaroglu (1968) undertook a programme of laboratory based research. Through physical analysis of the phenomena a theoretical relationship was obtained (equation 105).

$$\Phi_b = g_4 \Psi \qquad ....105$$

Where Ψ is the shear intensity parameter (equation 106), Φ_b is the transport parameter (equation 107) and g_4 is a functional relationship which was to be obtained using experimental data.

$$\Psi = {(s-1)d}\Big/{S_o R} \qquad ....106$$

$$\Phi_b = \frac{C_v VR}{\sqrt{(s-1)gd^3}} \qquad ....107$$

TABLE 14 : DATA USED BY Graf and Acaroglu (1968)

Investigator	Conduit Configuration	No. of Obs.	d_{50} (mm)	S.G.
Ismail (1952)	0.27 × 0.076m Flume	60	0.091 - 0.147	2.65
Wilson (1965)	0.0937 × 0.0937 Flume	67	0.710	2.65
Acaroglu (1968)	0.076m ∅ Pipe	123	2.00 - 2.78	2.67
Gilbert (1914)	Various	577	0.305 - 1.710	2.69
Guy et al (1966)	2.41 × 0.61m Flume 0.61 × 0.76m Flume	219	0.19 - 0.93	2.65
Ansley (1963)	0.153 × 0.153 Flume	26	0.223	2.65
Einstein (1944)	Natural River	81	0.900	2.67
Kriegel and Bauer (1966)	0.0535m ∅ Pipe	129	1.530	1.38 - 1.43

The data used to obtain the functional relationship, g_4, were gained from a number of sources; Ismail (1952), Wilson (1965), Acaroglu (1968), Gilbert (1914), Guy et al (1966), Ansley (1963), Einstein (1944) and Kriegel and Bauer (1966). The data used are summarised in Table 14. The relationship generated is illustrated in equation 108.

$$\Phi_b = 10.39\Psi^{-2.52} \quad \text{or} \quad \frac{C_v VR}{\sqrt{(s-1)gd^3}} = 10.39\left(\frac{(s-1)d}{S_o R}\right)^{-2.52} \qquad ....108$$

In terms of C_V the relationship takes the form of equation 109.

$$C_v = 5.32\times10^{-2}\lambda_c^{2.52}\left(\frac{d}{R}\right)^{-1.02}\left(\frac{V^2}{g(s-1)R}\right)^{2.02} \qquad ....109$$

Perrusquía (1991 & 1992)

With the aim of analysing the flow conditions which characterise flume traction in pipe channels, and their relationship to sediment transport and flow resistance, Perrusquía (1991 & 1992) initiated a programme of laboratory experiments. These experiments were conducted over continuous erodible beds in 154mm, 225mm and 450mm diameter pipes flowing part full. The sediments used were in the d_{50} range 0.72mm - 2.5mm, had specific gravities in the range 2.59 - 2.65 and were transported as bed-load in all tests. Theoretical and empirical analysis of the resultant data (for the 154mm and 225mm diameter studies only) resulted in the generation of equation 110.

$$\Phi_b = 46\times10^3\Theta_b^{2.9}D_*^{-1.2}d_{50}t_r^{-0.62} \qquad ....110$$

Where Θ_b, the dimensionless shear stress, and Φ_b, transport parameter, are determined using equations 111 and 112 respectively;

$$\Theta_b = \frac{R_b S_o}{(s-1)d_{50}} \qquad ....111$$

$$\Phi_b = \frac{q_b}{\sqrt{\left(g(s-1)d_{50}{}^3\right)}} \qquad ....112$$

Application of other laboratory data to the relationships obtained by Perrusquía (1991 & 1992) by other researchers (Ab. Ghani, 1993 & May 1993) has indicated that the relationship does not perform well outside the relatively low (by laboratory standards) sediment transport concentrations (36 - 408ppm).

Nalluri and Alverez (1992)

Based on sediment transport experiments over loose and rigid beds (10.5% > y_s/D > 39.2%) in a 154mm diameter pipe flowing part full, Nalluri and Alverez (1992) undertook analysis with the aim of obtaining relationships which could be used to predict the sediment transport rate over a deposited bed. Sediment d_{50} values were in the range 0.4mm - 5.1mm and had an average specific gravity of 2.55. For transport over a loose bed the sediment transport rate was expressed in terms of a transport parameter,Φ_b,and a flow parameter, Ψ_b, similar to the form used by Graf and Acaroglu (1968), as illustrated in equation 113;

$$\Psi_b = 9.931\Phi_b^{-0.123} \quad ....113$$

Additionally, for transport over flat rigid beds Nalluri and Alvarez (1992) obtained two relationships based on multiple regression analysis of dimensionless groups of parameters. The relationships obtained are illustrated in equations 114 (rigid) and 115 (loose);

$$\frac{\tau_b}{\rho(s_s - 1)gd} = 1.6C_v^{0.64}\left(\frac{d}{R_b}\right)^{-1.27}\lambda_{sb}^{0.62} \quad ....114$$

$$\frac{\tau_b}{\rho(s_s - 1)gd} = 0.26C_v^{0.63}\left(\frac{d}{R_b}\right)^{-1.32}\left(\frac{y_o}{P}\right)^{-0.40}\lambda_{sb}^{0.35} \quad ....115$$

The transport concentration for the test undertaken with rigid beds was in the range $112 < C_V < 677$ppm and for loose beds the range was $2 < C_V < 131$ppm.

May (1993)

In an extension of earlier work undertaken at HR Wallingford (May et al., 1989) May (1993) investigated transport of solids over significant depths of sediment deposits (13 - 27% of the pipe diameter) in a 450mm ID concrete pipe. Sediments with a d_{50} range of 0.47 - 0.73mm were used (average S.G. = 2.64), and were transported as bed-load in all tests. A semi-empirical transport relationship, primarily evolved from the Shields parameter, based on the shear stress acting on the sediment bed and an active layer concept in which the bed-load transport is hypothesised to occur. The first step in the methodology is to calculate the particle Reynolds number, R_{*c}, and the transition factor, θ, which is given in equations 116 and 117 respectively;

$$R_{*c} = \left(\frac{\lambda_c}{8}\right)\left(\frac{Vd_{50}}{\nu}\right) \quad ....116$$

$$\theta = \frac{\exp\left(\frac{R_{*c}}{12.5}\right) - 1}{\exp\left(\frac{R_{*c}}{12.5}\right) + 1} \quad ....117$$

The core of the methodology is the calculation of the transport parameter, η, (equation 118);

$$C_v = \eta\left(\frac{W_b}{D}\right)\left(\frac{D^2}{A}\right)\left(\frac{\theta\lambda_g V^2}{8g(s-1)D}\right) \quad ....118$$

Values for η are then selected from a functional relationship in Table 15, based on the sediment mobility number, F_S, (equation 119).

$$F_s = \sqrt{\frac{\theta\lambda_g V^2}{8g(s-1)d_{50}}} \quad ....119$$

TABLE 15 : DETERMINATION OF η (May, 1993)

$F_s \leq 0.100$	$\eta = 0$
$0.100 < F_s \leq 0.225$	$\eta = 1.6 \times (F_s - 0.1)$
$0.225 < F_s \leq 0.400$	$\eta = 0.2 + 2.13(F_s - 0.225)^{0.6}$
$0.400 < F_s < 0.650$	0.95

Tests were undertaken in a 21m long 450mm diameter concrete pipe, with velocities in the range 0.4m/s to 1.3m/s, and with y/D varying between 50% and 100%.

Ackers (1984 and 1991)

Based on earlier work undertaken on sediment transport in alluvial channels (Ackers and White, 1973) Ackers (1984) produced a sediment transport methodology for transport in pipes, culverts and open topped channels. The methodology may be used to estimate total sediment load, or as bed-load or suspension (Ackers, et al., 1994).

The approach utilises the original Ackers-White sediment transport methodology, in addition to the Colebrook-White friction factor. The core of the approach is a relationship which relates the non-dimensional transport parameter, G_{gr}, to the sediment mobility number, F_{gr}, which represent the flow velocity and the particle characteristics respectively (equation 120).

$$G_{gr} = H\left(\frac{F_{gr} - A_{gr}}{A_{gr}}\right) \qquad ....120$$

Where F_{gr} and A_{gr} are determined using equations 121 and 122 respectively;

$$F_{gr} = \left(\frac{u_*^n}{\sqrt{g(s-1)d}}\right)\left(\frac{V^{1-n}}{\left(\sqrt{32}\log_{10} 12 \frac{R}{d}\right)^{1-n}}\right) \qquad ....121$$

$$A_{gr} = 0.14 + \left(\frac{0.23}{\sqrt{D_{gr}}}\right) \qquad ....122$$

Where A_{gr} is the value of the mobility number at the threshold of movement and D_{gr}, the dimensionless grain size, which may be obtained via equation 123.

$$D_{gr} = \left(g\frac{(s-1)}{v^2}\right)^{1/3} d \qquad ....123$$

The parameter H, m and n are coefficients, which are related to D_{gr}, and are determined using equations 124, 125 and 126 when the sediments in transport are fine ($D_{gr} < 60$).

$$n = 1.00 - 0.56\log_{10} D_{gr} \qquad ....124$$

$$m = 1.34 + \frac{9.66}{D_{gr}} \qquad ....125$$

$$\log_{10} H = 2.86 \log_{10} D_{gr} - \left(\log_{10} D_{gr}\right)^2 - 3.53 \qquad ....126$$

Where sediments are coarse ($D_{gr} > 60$); $n = 0.00$, $A_{gr} = 0.17$, $m = 1.50$ and $H = 0.25$.

This methodology was then further developed (Ackers, 1991), largely through changes in the determination of coefficients. The volumetric sediment transport concentration is calculated using equation 127;

$$C_v = J\left(W_e \frac{R}{A}\right)^{\alpha} \left(\frac{d}{R}\right)^{\beta} \lambda_c^{\gamma} \left(\frac{V}{\left[g(s-1)R\right]^{-½}} - K\lambda_c^{\delta}\left(\frac{d}{R}\right)^{\varepsilon}\right)^{m} \qquad ....127$$

The coefficients m, J, α, β, γ, K, δ and ε, may be determined using equations 128, 129, 130, 131, 132, 133, 134, 135, and 136 respectively;

$$m = 1.67 + \frac{6.83}{D_{gr}} \qquad ....128$$

$$\log_{10} H = 2.79 \log_{10} D_{gr} - 0.98\left(\log_{10} D_{gr}\right)^2 - 3.46 \qquad ....129$$

$$J = \frac{8^{\left(\frac{n(1-m)}{2}\right)} H}{11.3^{m(1-n)} A_{gr}^{m}} \qquad ....130$$

$$\alpha = 1 - n \qquad ....131$$

$$\beta = \frac{(10 - 4m - mn)}{10} \qquad ....132$$

$$\gamma = \frac{n(m-1)}{2} \qquad ....133$$

$$K = 11.3^{(1-n)} g^{n/2} A_{gr} \qquad ....134$$

$$\delta = -{}^{n}\!/_{2} \qquad ....135$$

$$\varepsilon = \frac{4+n}{10} \qquad ....136$$

This methodology may only be used to calculate the volumetric sediment transport concentration, C_V, where a suitable value has been found for the effective transport width, W_e. Several laboratory based researchers (Ackers, 1984, CIRIA, 1987 and Ackers, 1991) have proposed different methods for obtaining W_e, these are listed in Table 16.

Although the Ackers model was originally proposed as a total load model, it has been recommended for application to bed-load or suspended load applications (Ackers et al., 1994 and Butler et al., 1996a and b)

TABLE 16 : DETERMINATION OF W_e FOR Ackers (1984 and 1991)

Ackers (1984)	$W_e = D$
CIRIA (1987)	W_e = the bed width at $y_d/D = 10\%$
Mat Suki & Nik Hassan (1990)	$W_e = 10d_{50}$
Ackers (1991)	$W_e = 0.04D$ when $y_d/D = 1\%$
Ackers (1994)	$W_e = 0.5W_b$ when $y_s/D > 10\%$
Ackers et al (1994)	$W_e = \left(0.2 + 3.33\left(\frac{y_s}{D} - 0.01\right)\right)W_b$ when $1\% \le y_s/D \le 10\%$ & $W_e = 0.5W_b$

Ab Ghani (1993)

Parallel to tests undertaken at the limit of deposition at the University of Newcastle and HR Wallingford, Ab Ghani (1993) carried out a series of tests, investigating sediment transport over a deposited bed. The sediment size used was in the range 0.93mm - 8.3mm in pipes of 154 - 450mm internal diameter. The relationship obtained, via multiple regression of dimensionless groups, is illustrated below in equation 137;

$$C_v = 0.355\left(\frac{W_b}{y_o}\right)^{1.12}\left(\frac{D}{d_{50}}\right)\lambda_c^{1.94}\left(\frac{V^2}{g(s-1)D}\right)^{3.12} \qquad ....137$$

Where y_o is the depth of flow over the sediment bed and λ_c is the composite friction factor which is defined in equation 138;

$$\lambda_c = 0.0014\left(\frac{W_b}{y_o}\right)^{0.34}\left(\frac{R}{d_{50}}\right)^{0.24} D_{gr}^{0.54} C_v^{-0.04} \qquad ....138$$

May (1994)

TABLE 17 : DETERMINATION OF η (May, 1994)

$F_s \le 0.100$	$\eta = 0$
$0.100 < F_s \le 0.225$	$\eta = 1.2(F_s - 0.100)$
$0.225 < F_s \le 0.275$	$\eta = 0.15 + 9.0(F_s - 0.225)$
$0.275 < F_s \le 0.400$	$\eta = 0.60 + 3.2(F_s - 0.275)$
$0.400 < F_s \le 0.700$	$\eta = 0.15 - (F_s - 0.400)$
$0.700 < F_s \le 0.800$	0.7

Based on an evaluation of existing laboratory based sediment transport methodologies for transport over a deposited bed (Ackers et al., 1994), May (1994) updated and enhanced earlier work undertaken at HR Wallingford. The evaluation highlighted the limited data base on which earlier relationships obtained at HR Wallingford had been established (May, 1993) as the tests were undertaken in a single sized pipe (450mm ID concrete). Based on this consideration the applicability was widened by modifying the relationship between the transport parameter, η, and the mobility number, F_s. The modified relationship between η and F_s is shown in Table 17

Perrusquía & Nalluri (1995)

Perrusquía and Nalluri (1995) extended earlier work (Perrusquía 1991 & 1992) by including the 450mm diameter pipe data, obtained at HR Wallingford, using sands with a d_{50} of 0.73mm. The inclusion of these results (9 tests) produced the relationship shown in equation 139 (r^2=0.78).

$$\Phi_b = 0.1282\Theta_g^{2.6}D_*^{0.39}\left(\frac{d_{50}}{y}\right)^{-0.79}\left(\frac{B}{y}\right)^{0.67} \qquad ....139$$

Where Θ_g, the grain mobility number, is determined using equation 140;

$$\Theta_b = \frac{\tau_b/\rho}{(g(s-1))d_{50}} \quad \left(= u_{*,g}^2\right) \qquad ....140$$

This relationship was then validated using data collected as part of three separate studies Álverez (1990), Ab. Ghani (1993) and May (1989 & 1993), some of which used the same test rigs. Table 18 gives details of these studies, along with that of Perrusquía (1991 & 1992).

TABLE 18 : RANGES OF EXPERIMENTAL DATA USED BY Perrusquía and Nalluri (1995)

Researcher	Álverez, (1990)	Ab. Ghani (1993)	May ('89 & '93)	Perrusquía (1991 & 1992)		
Laboratory	Newcastle	Wallingford	Wallingford	Chalmers	Newcastle	Wallingford
Pipe ∅ (mm)	154	450	300 & 450	225	154	450
d_{50} (mm)	0.53 - 2.9	0.73	0.47 & 0.72	0.9 & 2.5	1.00	0.73
Pipe Material	PVC	Concrete	Concrete	Concrete	PVC	Concrete
No. Of Tests	20	23	52	48	9	9
F_r	0.40 - 0.71	0.28 - 0.97	0.46 - 1.43	0.39 - 0.85	0.45 - 0.73	0.33 - 0.55
Θ_g ($\times 10^{-4}$)	274 - 546	431 - 2499	439 - 4082	410 - 1042	468 - 772	629 - 1218
Φ_b ($\times 10^{-4}$)	12 - 337	166 - 10830	91 - 20293	15 - 684	76 - 259	245 - 1693
C_v	13 - 128	21 - 1036	12 - 1187	36 - 408	82 - 277	38 - 303

Application of similar regression analysis of the same dimensionless groupings as Perrusquía (1991 & 1992), on only the validation data sets, produced the relationship illustrated in equation 141 (r^2=0.92).

$$\Phi_b = 0.0173\Theta_g^{2.3}D_*^{0.68}\left(\frac{d_{50}}{y}\right)^{-0.96}\left(\frac{B}{y}\right)^{0.88} \qquad ....141$$

Further application of this analysis methodology to the entire data set (161 observations) generated equation 142 (r^2=0.91).

$$\Phi_b = 0.0143\Theta_g^{2.2}D_*^{0.38}\left(\frac{d_{50}}{y}\right)^{-1.11}\left(\frac{B}{y}\right)^{0.78} \qquad ....142$$

The work of Perrusquía and Nalluri (1995) represents an advancement as it brings together six series of comparatively varied experiments, and forms a relationship which appears to perform well on laboratory data. However, it remains to be seen how well this relationship can perform in 'the field'.

4.5 Summary of Laboratory Based Sediment Transport Methodologies

It is beyond the scope of this study to provide an in-depth analysis of the experimental and analytical procedures employed by all researchers in the work undertaken investigating sediment transport at the limit of deposition and over a deposited bed. However, other researchers have completed such studies, notably Ackers et al. (1994) and this work is reported here.

4.5.1 Limit of Deposition - Summary

Relationships were analysed which were considered to be the most up to date and had the best experimental backing, the methods selected were;

1. Macke (1982)
2. May, Brown, Hare and Jones (1989)
3. May (1993)
4. Mayerle, Nalluri and Novak (1991)
5. Nalluri and Ab. Ghani (1993)
6. Nalluri, Ab. Ghani and El-Zeamey (1993)
7. Ab. Ghani (1993)
8. Nalluri, Ab. Ghani and El-Zaemey (1994)

Ackers et al. (1994) tested the relationships by applying them to the data sets, and then comparing the predicted and measured transport concentrations. In evaluating each set of equations a statistical method was used which avoids the biasing of data towards large results. The results were expressed in terms of a mean value and the standard deviation of the ratio, r, between the predicted and measured sediment concentrations, C_V. Equation 143 shows the relationship used to calculate the mean, r_m;

$$r_m = \exp\left(\frac{1}{n}\sum_{i=1}^{n}\left(\ln r_i\right)\right) \qquad ....143$$

Where;n = The number of ratios

r_i = The ratio Predicted C_V : Measured C_V

The standard deviation of the ratio, σ_m, can then be calculated using equation 144;

$$\sigma_r = \exp\left(\sqrt{\frac{1}{n}\sum_{i=1}^{n}\left(\ln r_i - \ln r_m\right)}\right) \qquad ....144$$

The value of r_m one standard deviation below and above the mean may then be determined using equations 145 and 146 respectively.

$$r_{-\sigma} = \frac{r_m}{\sigma_r} \qquad ....145$$

$$r_{+\sigma} = r_m \sigma_r \qquad ....146$$

TABLE 19 : LIMIT OF DEPOSITION DATA USED BY Ackers et al. (1994)

Data Set	Pipe ∅ (mm)	k_o (mm)	Sediment d_{50} (μm)	Specific Gravity	y_o/D	Flow Velocity (m/s)	C_v
1 (Macke (1982))	192, 290, 445	smooth (~0.003)	160, 370	2.63	0.20 - 0.90	0.44 - 1.21	3.7 - 1700
2 (May (1982))	77, 158	smooth (~0.003)	570 - 7900	2.65	0.37 - 1.00	0.45 - 1.19	6.3 - 2110
3 (May et al (1989))	299	0.15	720	2.62	0.49 - 1.00	0.50 - 1.22	0.3 - 440
4 (May (1993) & Ab. Ghani (1993))	450	0.14	730	2.63	0.49 - 0.75	0.24 - 0.86	1.6 - 38
5 (Ab. Ghani (1993))	154	smooth (~0.003)	930 - 9300	2.54 - 2.59	0.16 - 0.76	0.24 - 0.86	38 - 1450
6 (Ab. Ghani (1993))	305	0.53	970 - 8300	2.53 - 2.58	0.18 - 0.77	0.41 - 1.00	1 - 920
7 (Ab. Ghani (1993))	305	1.34	2000 - 8300	2.53 - 2.57	0.24 - 0.71	0.24 - 0.71	6.7 - 403

Details of the data sets used are summarised in Table 19 and the validation results are shown in Table 20.

As the results of the comparison study show, no single relationship gives good results for all of the data sets investigated (i.e. $r_m \approx 1.0$, and $\sigma_r \approx 0.0$). Ackers et al. (1994) notes that the HR Wallingford Results (May, et al 1989 & May, 1993) fit best where $0.5 \leq y/D \leq 1.0$, whilst the contrary is the case for the relationships obtained at the University of Newcastle-Upon-Tyne (Mayerle et al, 1991, Nalluri and Ab. Ghani, 1993 & Nalluri, et al (1994) Ab. Ghani, 1993). Based on the results of the comparison it is recommended that in the selection and application of these relationships the one chosen should be that where the laboratory set-up matches the application as closely as possible.

TABLE 20 : RESULT OF EVALUATION BY Ackers et al. (1994) FOR SEDIMENT TRANSPORT AT THE LIMIT OF DEPOSITION

Data Set	No. of Tests	Mean of Prediction Ratio & *(Standard Deviation of Ratio)*							
		Method 1	Method 2	Method 3	Method 4	Method 5	Method 6	Method 7	Method 8
(1a)	60	1.73 *(2.95)*	0.160 *(3.70)*	0.214 *(3.86)*	0.013 *(4.44)*	0.111 *(3.84)*	0.136 *(3.87)*	0.109 *(3.86)*	0.143 *(3.91)*
(1b)†	22	1.23 *(3.20)*	0.389 *(3.91)*	0.431 *(4.27)*	0.052 *(4.08)*	0.331 *(3.18)*	0.357 *(4.51)*	0.320 *(3.34)*	0.415 *(3.29)*
(2)	57	0.536 *(3.94)*	1.06 *(1.34)*	0.958 *(1.41)*	0.551 *(2.95)*	1.78 *(1.69)*	0.914 *(2.37)*	1.90 *(1.74)*	1.03 *(1.55)*
(3)	48	2.13 *(1.56)*	1.03 *(1.60)*	1.26 *(1.54)*	0.478 *(1.61)*	2.57 *(1.56)*	1.83 *(2.33)*	2.46 *(1.56)*	1.83 *(1.78)*
(4)	27	0.806 *(1.69)*	0.296 *(2.65)*	0.596 *(1.65)*	0.128 *(1.98)*	0.934 *(1.60)*	0.500 *(2.39)*	0.795 *(1.68)*	8.70 *(1.79)*
(5)	39	0.022 *(3.35)*	0.150 *(3.55)*	0.028 *(8.59)*	0.217 *(3.34)*	0.525 *(2.30)*	0.410 *(3.14)*	0.513 *(2.34)*	0.655 *(2.20)*
(6)	71	0.087 *(3.01)*	0.051 *(4.42)*	0.031 *(4.86)*	0.234 *(2.18)*	1.21 *(1.47)*	0.376 *(1.80)*	1.02 *(1.50)*	0.792 *(1.43)*
(7)	30	0.164 *(2.35)*	0.065 *(2.93)*	0.025 *(6.43)*	0.280 *(1.50)*	2.15 *(1.33)*	0.428 *(1.43)*	1.73 *(1.33)*	1.16 *(1.31)*
(1) - (7)	332	0.350 *(6.44)*	0.218 *(5.02)*	0.167 *(8.05)*	0.171 *(5.07)*	0.875 *(3.67)*	0.479 *(3.40)*	0.816 *(3.65)*	0.700 *(2.99)*
(2) - (7)	272	0.246 *(6.13)*	0.234 *(5.28)*	0.158 *(9.13)*	0.302 *(2.63)*	1.38 *(2.05)*	0.633 *(2.71)*	1.27 *(2.11)*	0.994 *(1.84)*

†This data set contains only those data pertaining to the 370μm sand in data set (1a) obtained by Macke (1982)

4.5.2 Transport Over a Sediment Bed - Summary

Ackers et al (1994) selected what was deemed to be the most reliable of the existing laboratory relationships available for sediment transport over a 'deposited' bed (either loose or rigid). Four methods were selected, along with their variants;

1. Ackers (1984) ($W_e = W_b$)
2. Ackers (1984) (W_e calculated using Ackers et al (1994))
3. Ackers (1991) ($W_e = W_b$)
4. Ackers (1991) (W_e calculated using Ackers et al (1994))
5. Graf and Acaroglu (1968)
6. May (1993)
7. Ab Ghani (1993)
8. May (1994)

Before the evaluation of each of these relationships could begin, consideration had to be given to two factors which relate to the presence of the sediment bed.

1. Selection of a single method for the estimation of the sediment bed roughness. The method selected was that developed by May (1993), equation 147

$$\lambda_c = \frac{P_o \lambda_o + W_b \lambda_b}{P_o + W_b} \qquad ....147$$

2. Where bed-forms were known to exist a method had to be selected to represent the bed characteristics. For this the method proposed by May (1993) was selected, which involves calculating the sediment transport concentration and flow resistance based on average dimensions of individual dunes.

As both these factors were resolved by application of methods developed by May (1993) it is evident that the appraisal of the sediment transport equations by Ackers et al (1994) may be biased towards the transport methodology developed by May (1993).

Each of the transport relationships were tested using 8 sets of laboratory data and the results were expressed in terms of a mean prediction ratio, r_m, and the standard deviation ratio σ_r. A summary of the data sets used for appraisal is given in Table 21 and the results are given in Table 22.

TABLE 21 : TRANSPORT OVER A DEPOSITED BED DATA CHARACTERISTICS

Data Set	Pipe Ø (mm)	k_o (mm)	Sediment d_{50} (μm)	S.G.	y_o/D	y_s/D	Flow Velocity (m/s)	C_v
1 (May et al . (1982))	299	0.15	720	2.62	0.20 - 0.90	< 0.162	0.61 - 1.52	280 - 1190
2 (May et al . (1982))	299	0.15	720	2.62	0.37 - 1.00	< 0.050	0.52 - 1.41	23 - 360
3 (Alvarez (1989))	154	0.009	530 - 2900	2.65	0.49 - 1.00	0.11 - 0.39	0.28 - 0.63	2.3 - 128
4 (Perrusquía (1991))	225	0.15	900 - 2500	2.65	0.49 - 0.75	0.2 - 0.4	0.29 - 0.67	28 - 408
5 (Perrusquía (1992))	225	0.06	900 - 4000	2.65	0.16 - 0.76	<0.20	0.48 - 0.67	96 - 252
6 (May (1993))	450	0.14	470 - 730	2.63	0.18 - 0.77	0.12 - 0.29	0.40 - 1.32	3.5 - 1280
7 (May (1993) & Ab. Ghani (1993))	450	0.14	730	2.63	0.24 - 0.71	<0.009	0.5 - 0.84	3.6 - 35
8 (Ab. Ghani (1994))	450	0.14	730	2.63	0.24 - 0.71	0.12- 0.23	0.50 - 1.21	21 - 672

Analysis of the results showed that, overall, each of the relationships performed better than those which were formulated for transport at the limit of deposition. Ackers et al. (1994) hypothesise that this may be due to the variation of the effective bed width with flow conditions at the limit of deposition, whereas when transport over a deposited bed is considered, the effective bed width is constrained by the geometry of the bed.

The relationships based on work undertaken in alluvial channels (Ackers 1984 & 1991) were seen to perform the poorest and the empirical relationships obtained by Graf and Acaraglu (1968), May (1993) and Ab. Ghani (1993) all performed equally well, with the relationship obtained at HR Wallingford (May, 1993) performing slightly better, although its application is a great deal more complex. Additionally it was found the applicability was limited as it was based on data from only one size of pipe, based on this consideration the relationship was modified (May, 1994) and its performance was slightly improved.

TABLE 22 : SEDIMENT TRANSPORT OVER A DEPOSITED BED MODEL PERFORMANCE (After Ackers et al., 1994)

Data Set	No. of Tests	Mean of Prediction Ratio & *(Standard Deviation of Ratio)*							
		Method 1	Method 2	Method 3	Method 4	Method 5	Method 6	Method 7	Method 8
(1)	12	2.00 *(1.34)*	0.926 *(1.29)*	2.15 *(1.41)*	0.996 *(1.29)*	1.03 *(1.52)*	1.456 *(1.29)*	2.67 *(1.61)*	1.18 *(1.39)*
(2)	27	1.58 *(1.69)*	0.633 *(1.68)*	1.62 *(1.79)*	0.648 *(1.77)*	1.16 *(2.00)*	0.959 *(1.58)*	0.860 *(2.54)*	0.843 *(1.49)*
(3)	30	0.872 *(3.34)*	0.587 *(2.81)*	0.323 *(4.75)*	0.221 *(4.43)*	3.00 *(1.90)*	1.80 *(2.58)*	2.46 *(1.75)*	1.35 *(2.59)*
(4)	43	0.225 *(6.43)*	0.135 *(5.39)*	0.039 *(7.00)*	0.027 *(5.90)*	0.463 *(2.43)*	1.21 *(2.16)*	0.505 *(2.38)*	0.932 *(2.19)*
(5)	10	0.752 *(1.81)*	0.403 *(1.96)*	0.258 *(3.49)*	0.138 *(3.78)*	0.648 *(2.52)*	1.63 *(1.35)*	0.817 *(2.09)*	1.31 *(1.46)*
(6)	65	0.17 *(2.21)*	0.748 *(2.14)*	1.15 *(2.28)*	0.738 *(2.31)*	1.27 *(2.49)*	0.985 *(1.74)*	1.16 *(2.03)*	0.914 *(1.82)*
(7)	6	1.45 *(1.18)*	0.519 *(1.19)*	1.36 *(1.18)*	0.488 *(1.19)*	1.27 *(1.42)*	0.972 *(1.20)*	0.340 *(1.29)*	0.951 *(1.43)*
(8)	15	1.27 *(1.24)*	0.795 *(1.24)*	1.26 *(1.32)*	0.786 *(1.32)*	1.30 *(1.53)*	1.04 *(1.48)*	1.06 *(1.47)*	0.975 *(1.65)*
(1) - (8)	208	0.848 *(3.65)*	0.485 *(3.32)*	0.485 *(6.46)*	0.286 *(5.73)*	1.11 *(2.63)*	1.18 *(1.95)*	1.04 *(2.49)*	0.998 *(1.95)*

Based on data collected in experiments monitoring sediment transport over loose beds (2% < y_s/D < 29%) Kleijwegt (1992) carried out a similar evaluation exercise. The tests were undertaken in a single sized pipe (152mm diameter) with full and part full flows transporting 3 sediment sizes (0.087mm, 0.2mm and 0.781mm) The results suggested that the equations obtained by Ackers (1984) and van Rijn (1984) performed well over continuous loose beds with bed-forms, whilst where no bed forms were present the relationships obtained by Engelund and Hansen (1967) and Graf and Acaroglu (1968) could be used.

4.6 Conclusion

Although Ackers et al. (1994) did carry out a considerable amount of work on comparison of the relationships, only limited tests were done with actual field data, due to availability. The field tests were not successful (May, 1995) as the data was not competent. Herein lies the problem, as it is clear from the literature that a considerable amount of time and expense has been invested in studies which aim to physically model the fundamentally complex hydraulics of sewers. The studies, which in general are similar, produce models which will not perform well on data other than that from which they were generated. If there is difficulty experienced in applying one model to data from another study, this raises significant questions about how this can be applied to 'real' sewer conditions.

However, the development of these models may be justified as they aim to address the fundamental principles which control sediment transport in pipes. Although, it is difficult to conceive how many of the parameters which influence sediment transport in real sewers (inputs to the system, upstream sediment characteristics, rainfall history etc.) may be represented in a laboratory study.

4.7 U.K. Sewer Design

Currently, most sewerage and drainage systems are designed to achieve a minimum 'self cleansing' velocity (or critical velocity) at least once each day (CIRIA, 1986). In the UK, BS 8005 (British Standards Institution, 1987) recommends a full pipe velocity of 1 m/s in order to ensure that a velocity of 0.75m/s is exceeded at least once each day on average. However, the critical self cleansing velocity chosen for sewer design does vary from country to country as shown in Table 23.

TABLE 23: INTERNATIONAL VARIATION IN CLEANSING VELOCITY

Country	Sewer Type	Min Velocity (m/s)	Conditions
USA	Foul Storm	0.6 0.9	Full to ½ full
Germany	-	1.5	Pipe full
UK	Storm, Foul or Combined	0.75 1.0	Pipe full

The use of self cleansing criteria for the design of sewers does not take into account the pipe size and the concentration of sediment. The critical velocity approach has been shown by Yao (1974), in an extension of work undertaken by Lynse (1969), to underdesign larger diameter sewers and overdesign those with smaller diameters, with respect to sedimentation. This is confirmed by Macke (1982), Thompson,

(1986) and Nalluri & Ab. Ghani (1993). Yao (1974) also showed that, where the flow is less than 40% of the height of the sewer, a design based on critical shear stress would typically supply a more efficient design. Generally, a minimum fluid/bed boundary shear stress of between 1 and 4N/m^2 is recommended. These results are confirmed by collaborative work carried out between Dundee and Hanover, in Germany, (Ashley et al., 1993) where bulk erosion of the bed has been observed in the range 1.5-2.0N/m^2, and Stotz & Krauth (1986) who estimated that erosion became significant in the range 2.0-4.0N/m^2. Laboratory studies using synthetic sewer sediments (Nalluri & Alvarez, 1992) found that material analogous with Type C sediment deposits eroded at 2.5N/m^2, whilst coarser sediments eroded in the range 6-7N/m^2.

To overcome this apparent problem in recent years a move has been made to standardise and update the design procedure in the U.K. (Ackers et al., 1994, May, 1995 and Butler et al., 1995a & 1995b). The principal changes in the design procedure have been implemented by recognising the effect the presence of sediment, both deposits and in transport, has on sewer hydraulics to obtain a self cleansing velocity unique to each pipe length under consideration. The self cleansing velocity obtained is that which meets each of 3 criteria;

1. The flow velocity which attains a grain shear stress sufficient to erode material from a inorganic deposited bed which may develop some cohesive-*like* strength. This criteria requires a bed shear stress (τ_b) $\geq$2.0 N/m^2 assuming the material concerned has a particle size of 1.00mm and the bed has an effective roughness (k_b) of 1.2mm. The equivalent full bore velocity is obtained using equation 148;

$$V_m = \sqrt{\frac{8\tau_b}{\rho\lambda_b}} \qquad \text{....148}$$

   Where λ_b is estimated using equation 149;

$$\lambda_b \cong \frac{1}{4\left(\log_{10}\left(\frac{k_{sb}}{3.7D}\right)\right)^2} \qquad \text{....149}$$

2. Transport a minimum concentration of material (fine grained and low density) in suspension. Based on the work undertaken by Macke (1982), the limiting velocity for this criterion may be estimated using equations 150 and 151;

$$V_m = \left(\frac{7.6\pi C_v (s-1) w_s^{1.5}}{\lambda_c^3}\right) \qquad \text{....150}$$

$$w_s = \frac{\sqrt{\left(9v^2 + d^2 g(s-1)(0.03869 + 0.0248d) \times 10^{-9}\right)} - 3v}{(0.11607 + 0.074405d) \times 10^{-3}} \qquad \text{....151}$$

3. A velocity must be specified which allows the transport of coarser, inorganic, granular material (grit) as bed-load at a rate sufficient to limit the depth of deposition to a specified proportion of the pipe diameter. Where transport is over a clean invert, the methodology employed is based on the work of May (1994) at the limit of deposition and is summarised in equation 152;

$$C_v = 3.03 \times 10^{-2} \left(\frac{D^2}{A} \right) \left(\frac{d_{50}}{D} \right)^{0.6} \left(1 - \frac{V_t}{V_L} \right)^4 \left(\frac{V^2}{g(s-1)R} \right)^{2.02} \qquad ....152$$

Where transport over a deposited bed is considered equation 153 is used

$$C_v = \eta \left(\frac{W_b}{D} \right) \left(\frac{D^2}{A} \right) \left(\frac{\theta \lambda_g V^2}{8g(s-1)D} \right) \qquad ....153$$

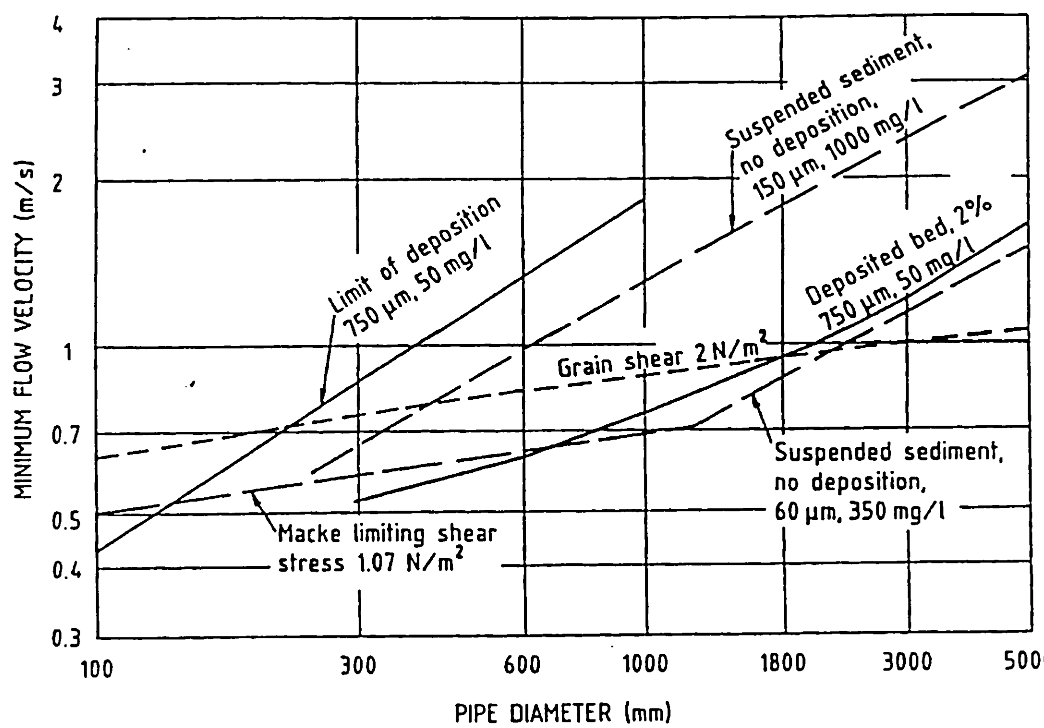

Figure 23 : Minimum Required flow for different sediment transport criteria (from Butler et al, 1996b)

Figure 23 illustrates each of the three design criteria graphically, in terms of the required full bore velocities for pipe diameters. The plot illustrates that different criteria govern the design of different pipe sizes. It is evident that for other than small pipes, design for transport at the limit of deposition will be restricted to steep sites, due to the high velocities required. For the majority of designs the design criteria for small pipes will be based on the erosion criteria for cohesive particles, with the larger pipe design being covered by the transport of material in suspension or as bed-load. The figure also illustrates how for some sewers a design which allows for some deposition may be the most economic, as substantiated by Nalluri & Ab. Ghani (1994).

4.8 Discussion

In over 100 years of investigating sediment transport in laboratory studies, significant progress has been made in the investigation of single sized non-cohesive dense spheres in a variety of test geometries, with predominately steady, uniform flows. However, little work has been undertaken in quantifying the parameters which affect sediment transport in sewers, such as; rainfall hyetographs, upstream characteristics, and the sediment supply rates and particle characteristics which are commonly experienced in sewers. Available sediment transport models have been shown to lack precision, even when evaluated in laboratory studies. However, despite this they are now the basis for a modified design procedure for self cleansing sewers.

The work of Skipworth (1996) is important as it has investigated the erosion and transport of a sediment which has comparable characteristics to that observed in sewers in unsteady flows. The application of the relationship proposed by Skipworth would be difficult, due to its calibration procedure. The work of Torfs (1995), which has resulted in a similar relationship to that obtained by Skipworth (1996), is important as it provides a valuable link between the alluvial and sewer sediment research.

The work reported in sections 4.3 "Transport at the Limit of Deposition in Pipes" and 4.4 "Transport Over a Deposited Bed" represent considerable advances in understanding the mechanisms controlling the transport capacity of flows in sewers, and other conduits. Much of this work may be valuable when undertaking work to prevent deposition in pipes (i.e. ensuring the transport capacity is not exceeded), but it is of less applicability for engineers attempting to predict the mass of sediments reaching treatment plants. To remedy this, the current project will seek to develop a model which can be used to estimate the actual transport of material at the bed in sewers rather than the transport capacity.

Perhaps the most important result of the laboratory based sediment transport investigations has been in highlighting the influence sediment deposits have on sediment transport capacity. The financial savings gained by allowing a limited amount of deposition in some sewers will possibly be substantial. Although, the presence of a sediment deposit in sewers can lead to pollution problems, which may lead to longer term financial costs, when sediments, and associated interstitial fluids, are eroded and enter the environment via COS's.

The work of Ackers et al. (1994) and Perrusquía and Nalluri (1995) in evaluating the mass of data collected in laboratory studies for transport at the limit of deposition (section 4.3) and over deposited beds (section 4.4) will prove valuable to this study. This being due the proposed relationships which have the best applicability to the widest range of data. These relationships will be applied to data collected in a real sewer as part of this project where data are available.

Chapter 5: Catchment Overview and Data Collection Procedures

This chapter gives details of the catchments in which most of the data collection was undertaken. The site selection procedures and data collection protocols are also discussed.

5.1 Catchment Details

This section gives a brief overview of the catchment and the Dundee sewer system in general. Whilst much of the details discussed herein have been noted by the author personally on various site visits to different parts of the system, most were described elsewhere (Ashley et al.,1992, Ashley, 1993, Ashley, 1994, Wotherspoon, 1994, Coghlan, 1995 and Rennet, 1995).

The City of Dundee is drained by a gravity combined sewerage system and historically discharged via more than 30, mostly untreated, outfalls into the Tay Estuary. Whilst the sewerage, at first glance, appears dendritic in pattern, the presence of over 250 flow control 'gates' means that there is potentially, and in practice normally a number of loops, by-passes and bifurcations in the main system as well as the secondary network. The situation is further complicated, for an operations engineer, by the ease with which gates can be moved by operations staff, or by the flow itself, and then disregarded indefinitely.

The core of the system dates from the nineteenth century, and is mainly ovoid or non-standard egg shape in construction, with some circular sections. The largest section is the central area interceptor, which is up to 1.8m in diameter. Some major sections in the system have been relined, or replaced in some cases, however there are still some sections where the fabric of the sewer is badly eroded.

Up until 1990 sewage flooding in the central area catchment had been a regular event, occurring once in every 2 to 3 years. This is largely due to the intrinsic nature of the sewer network and the geography of the city, whereby flows from the steeper catchments around the city centre are rapidly conveyed into the relatively flat lower lying central area. If a sufficiently intense storm is combined with a high tide, the uncontrolled tidal outfalls will be unable to convey the flows away and cause the system to back up, surcharge and eventually flood. Removal of sediment in the sewers in the city, following research in 1989, has so far alleviated flooding in the area, although some localised flooding does occur in the lower terrace.

The sewer catchment studied is that which drains into the main city centre interceptor and is recognised by the system operators as being the 'Central Area Catchment'. Flow from the higher ground around the city centre, the Law and Balgay Hills, are drained into the interceptor sewer via steep trunk sewers. Due to the complexity of the system, caused by the numerous flow control gates, many of which are half gates and can act as internal overflows during storms, the central area catchment has been considered as a number of sub-catchments (the division is not physical and is purely for hydraulic modelling convenience), these are listed in Table 24:

TABLE 24 : CONTRIBUTING CATCHMENTS FOR INTERCEPTOR SEWER

Sub Catchment	Population (× 1000)	Area (ha)	Land Use
Perth Rd.	4.800	164.9	T,I,P
Constitution Rd.	2.900	64.6	T,H,I,S,P
Hilltown	1.900	30.3	T,H,I,P
Dens Rd.	11.500	236.4	T,H,I,S,P
Dura St.	1.600	37.5	T,H,I,S,P
Albert St.	2.200	11.2	T,H,I,S,P
Hawkhill	0.280	6.8	T, I & P
Blackness	1.300	20.2	T,H,S & P
Polepark	5.800	159.9	T,H,S,P &I
Guthrie St	0.420	19.3	T & I
Lochee	0.200	14.2	T,I,S & P
City Centre	~5.300	~25	T,S & P
Totals	**37.24**	**909.6**	-

Land Use : T - Tenements / High Rise; H - Housing; S - Retail; I - Light Industry / Commercial; P - Park & Permeable Areas; H - Hospital

Of these, all but the Perth Road Sub-Catchment drain into the interceptor. Total flows in the catchment are approximately 6875 m^3/day (4479 m^3/day domestic and 2406 m^3/day industrial). It should be noted that the city centre is the main retail area, and as such has a somewhat transient population, consequently the population, and hence the flow, varies both on a micro and macro scale.

5.1.1 The Interceptor Sewer

The interceptor sewer begins in a chamber in which there is a gate, which can direct flows into the Dock system, or into the interceptor sewer. The total length of the interceptor, from its head to the outfall is approximately 2200m. It was constructed in the late nineteenth century, and has an average gradient of 0.7‰ in the study section. The interceptor sewer historically suffers from sediment problems, and deposits in excess of 300mm (~16% of the pipe height) are not uncommon.

The interceptor sewer is situated on a former river terrace, some 5m above high tide level in the Tay Estuary. The interceptor sewer is connected to an additional sewer

(Dock Street), which runs parallel at a lower level, via gates. Flows in the interceptor sewer can be diverted to the lower level at a number of points, in addition to the chambers mentioned above, to give some control over the flows in the sewer.

Hydraulic analysis of the system (Ashley, 1993) has shown that the flow regime is controlled by downstream conditions. For free surface conditions, flows were found to be always sub-critical. Cleaning of the sewer sediments has resulted, in the past, in the point of downstream control moving further towards the outfall. Cleaning also results in a lowering of the depth and an increase in the average velocity conditions. Typically during DWF, velocities are in the range 0.05 - 0.38 ms^{-1}, although during storms velocities can exceed $1.5ms^{-1}$.

5.2 Fieldwork

5.2.1 The Interceptor Sewer

The main aim of the field work undertaken in the Dundee sewerage network as part of this study, was to characterise the physical and pollutant properties of the material being transported at, or near, the bed in the system. The first stage in the fieldwork programme was to select suitable sites for data collection. In selecting field sites careful consideration had to be given to each of the following points;

- Was material transported near the bed at the site considered.
- Was there a sediment bed at the site.
- Was the contributing catchment representative of the catchment as a whole (e.g. not wholly industrial).
- Would entry to the site allow unrestricted access 24 hours per day.
- Was there sufficient area on the surface to allow temporary storage of fieldwork equipment.
- Would the internal characteristics of the study site have any unusual feature which would mean the data obtained were not representative.
- Was each study site sufficiently different to warrant separate studies.
- Would the presence of any of the test equipment unduly affect the operation of the sewer.

The presence of material moving near the bed was the most important factor affecting site selection for this project. As the Dundee sewer system is served by a number of silt traps, it was possible to use these to gain some indication of where material is being transported near the bed in the network. In conjunction with the sewer system operator, Tayside Regional Council Water Services Department, the following study sites were selected which met all of the required criteria.

1. Dens Brae Silt Trap, Trunk Sewer

2. Samuels Silt Trap, Interceptor Sewer
3. Constable Street Silt Trap, Interceptor Sewer

The location of each of the study sites is shown on the schematic sewer system plan (Figure 24) and is also illustrated on the location plan (Figure 25).

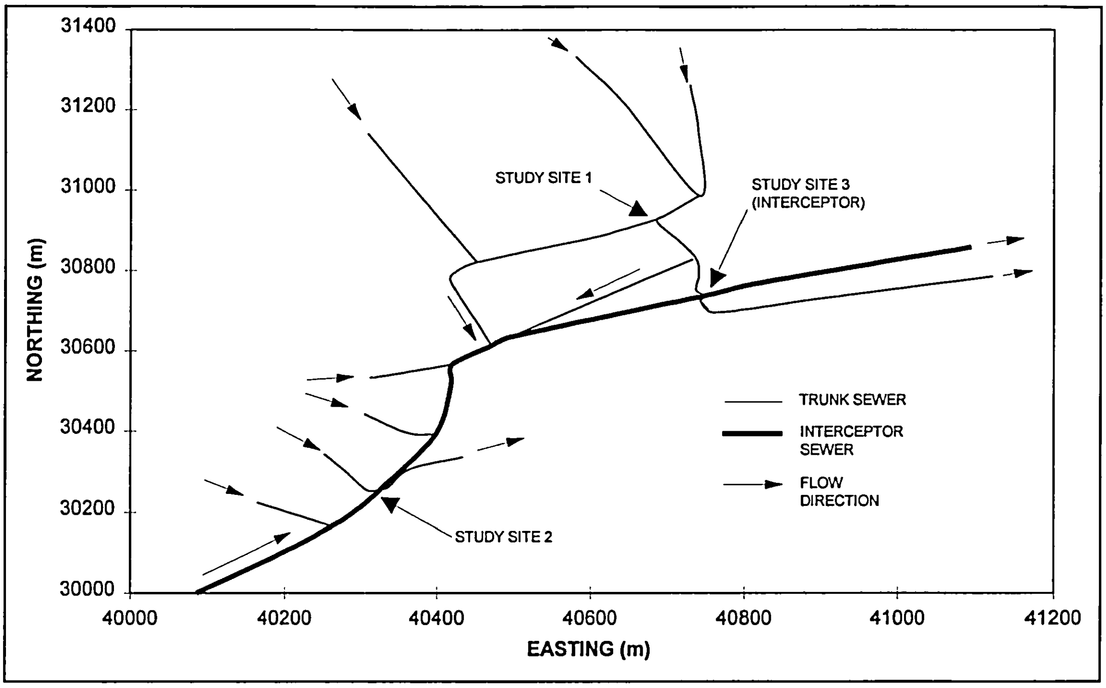

Figure 24 : Schematic sewer system plan

The sites selected for data collection as part of this study are not necessarily representative of sewer systems in the UK as a whole. However, they do present a microcosm of the sewerage system of Dundee.

Each of the 3 field sites selected are at silt traps in the system. This was essential since to trap material moving near the bed it is necessary to install a mechanism in the invert of the sewer. The use of silt traps as data collection sites avoided having to excavate a hole in the invert of the sewer as an artificial sewer could be built over the silt trap, and a hole created in the invert to house sediment traps. Each of the three test rigs constructed operated on the premise that the material moving near the bed is denser than the flow and will fall into any reasonable sized hole in the invert. Based on this, at each site, test rigs were constructed which spanned the silt traps, with sediment traps fitted to the invert in each case.

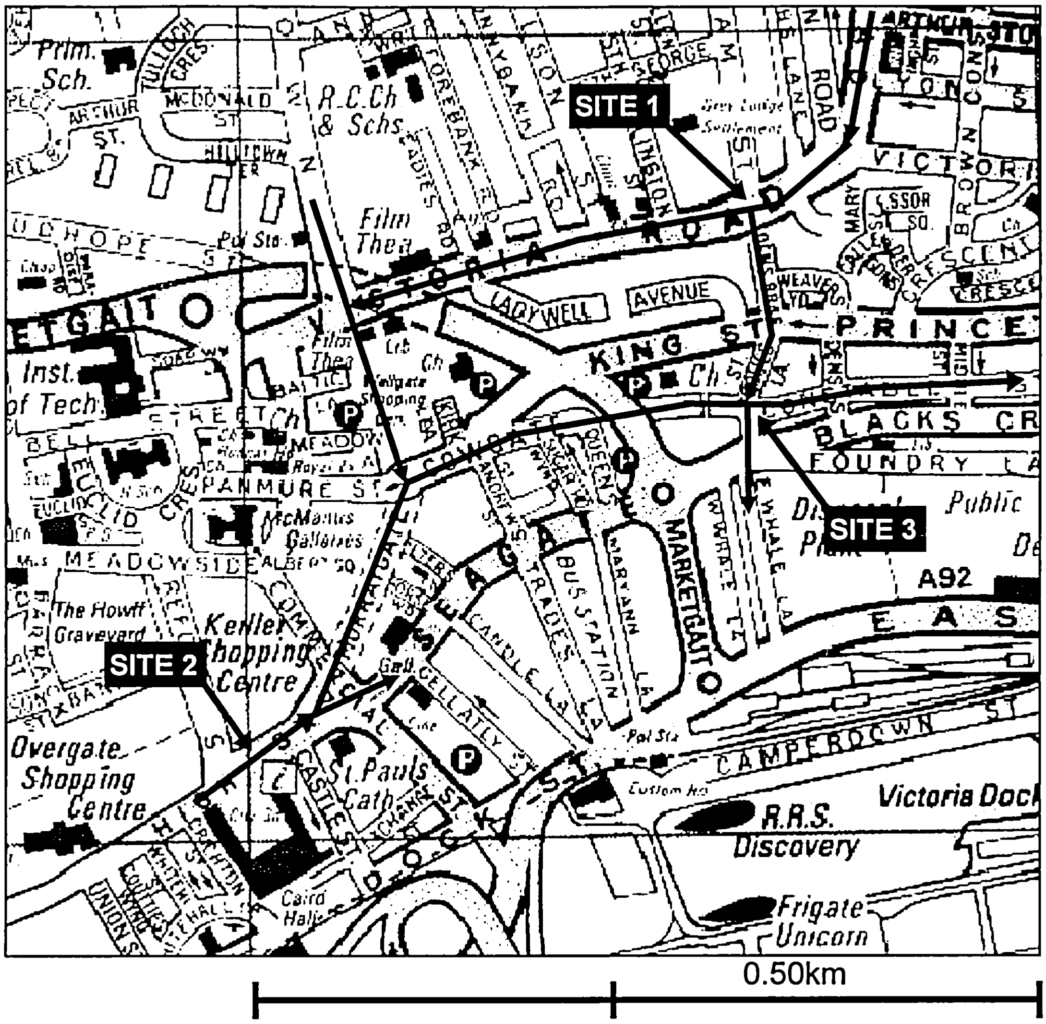

Figure 25 : Site Location Map# (For clarity some details have been omitted.)

5.2.2 Sample Collection

In sampling material transported near the bed using traps, it was first assumed that the material moves by saltating, sliding and/or rolling along the invert, in the classic (fluvial hydraulics) bed-load mode. Secondly it was assumed that it has a higher specific gravity than that of the flow. However, it is recognised that a small proportion of the material moving in suspension near the bed may also settle into the traps.

As some of the material is assumed to jump, or bounce, along the invert it is necessary to ensure that the length of the trap is sufficient to avoid material jumping over it. However, if it is too long it is possible that some of the material may not fall into the containers fitted in the invert due to circulatory flow patterns which will

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develop at the mouth of the sediment trap. To avoid this the sediment trap was compartmentalised at each of the sites to give a number of separate containers (5 or 6). This set-up has the added advantage of partially grading the material, since the upstream container, in theory, should collect the matter which has smaller saltation length, conversely the traps further downstream should contain material with longer saltation lengths. In a laboratory based study, Torfs (1995) observed, in a 400mm by 400mm rectangular flume with a 600mm invert trap, that up to 20mm above the bed "streamlines dive into the bed".

Although the methodology used for trapping the material moving near the bed is elementary, field based observations at Study Site 3 show that it does appear to operate efficiently. Similar methods have been employed by other researchers (Lin et al 1992a & 1992b & Bertrand-Krajewski et al, 1995) who based their work on a method developed by Hardwick and Willets (1991) in estuarine studies, and was developed separately by M^c^Gregor and Ashley (1990).

The size of the aperture at the top of the sediment trap was based on the calculation of the mean jump length (J_m) of sediment particles. The design was based on selecting a trap size which ensured a particle which has a mean jump length less than 25% of the total length of the trap (600mm & 700mm for the trunk and interceptor studies respectively) deposited in the trap. The mean jump length of the median inorganic bed-load material size was estimated using the method proposed by van Rijn (1984), equation 154 below.

$$J_m = 3D_*^{0.6}T^{0.9}d_{50} \qquad ....154$$

Where : J_m = The mean jump length.

d_{50} = Median particle diameter

D_* = Dimensionless particle diameter (equation 155)

$$D_* = d_{50}\left[\frac{(s-1)g}{v^2}\right]^{1/3} \qquad ....155$$

Where : v = Mean flow velocity

T = Transport stage parameter (equation 156)

$$T = \left(\frac{(u_*')^2-(u_{*cr})^2}{(u_{*cr})^2}\right) \qquad ....156$$

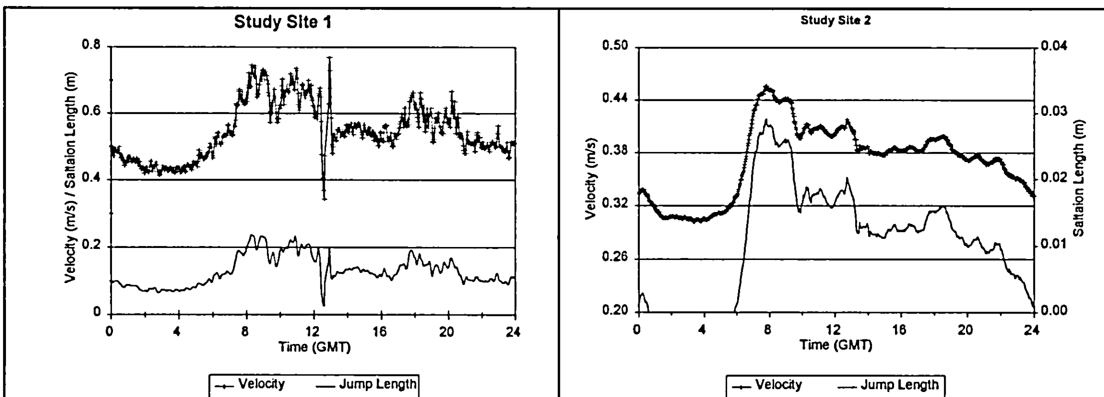
Where : u_{*cr} = Critical bed shear velocity

u_*' = Bed shear velocity

When using the above method it was assumed that the d_{50} size remained constant throughout the entire DWF diurnal period. The mean jump length estimations are shown below in Table 25, and Figures 26a and b show how the mean jump length (saltation length) for the d_{50} size varied throughout a 24 hour DWF period. The figures show that the mean jump length varies considerably throughout the period considered and that the parameter is dependent on flow velocity (and hence bed shear). The data also show that the mean jump length is noticeably larger in the trunk sewer due to the higher ambient velocity conditions. It is interesting to note that for the interceptor data the d_{50} particle has a saltation length of zero during the early hours of the morning, indicating deposition.

TABLE 25 : MEAN JUMP LENGTH DATA USING van Rijn (1984)

	D_{50} (mm)	Average J_m (24 Hours)	Average J_m (6am - 6pm)
Interceptor Sewer	1.4	0.011m	0.017m
Trunk Sewer	2.2	0.130m	0.157m



a Trunk Sewer

b Interceptor Sewer

Figures 26a & b : Saltation length variation throughout the daily flow pattern

In addition to the method used to collect samples of the material moving near the bed in the Dundee system, Ackers et al. (1994) recommend other methods;

1. Isolate and drain down a length of sewer, and attempt to make conclusions concerning the material which has been deposited on the invert, above any existing sediment bed.
2. To trace particle movement, coloured or radioactive sediment particles may be placed in their flow and their progress tracked.

These methods were not considered for use as part of this study, as the results would only supply very crude data concerning the physical characteristics of the material, and it would be difficult to obtain a reasonable estimation of the transport rate near the bed.

Other methods have, however, been used to collect samples of material moving near the bed, notably that employed by Verbanck (1994), Ristenpart (1993 & 1995) and Brombach and Wöhrle (1991). This method consisted of collecting samples via small diameter sampling hose located near the bed. This method was not the main method used in Dundee, as, although smaller sized particles would be sampled well, larger (faecal and sanitary) solids would not be represented. As the characteristics of sewage samplers prevent them from sampling heavy mineral particles and bulky gross solids. Therefore results obtained based on this method will represent the smaller particles (i.e. those which have a low specific gravity and those which can fit up the sampling hose) moving near the bed.

In all of the 3 studies undertaken, sewage samples were obtained using EPIC 1011[#] portable wastewater samplers. These obtain a sample by creating a partial vacuum in the sampling unit. The sewage is drawn along a small bore (usually 8mm internal diameter) hose to the sampling unit. The sewage is then passed to 1 of the 24 sampling bottles held in the base of the unit. At each of the sites the samples were normally programmed to take a set of 24 samples at pre determined intervals, after being started manually. Each sample obtained was usually 500ml in volume, although it was possible to vary this.

5.2.3 Flow Data Collection

At all of the study sites flow conditions were monitored using MONTEC[#] flow survey loggers. The units measure 'average' flow velocity by utilising the Doppler shift phenomena demonstrated by ultrasound waves. Depth is measured by a simple pressure transducer fitted in the base of the ultrasonic head. Full details of the operation of these units, and comparisons with other flow measuring devices, is available elsewhere (Ashley et al, 1992a & 1992b and Wotherspoon, 1994, Watt & Jefferies, 1995).

Prior to field installation, all loggers were checked and calibrated as accurately as possible in laboratory conditions. However, when on site the accuracy of the loggers does drift, and to remedy this the data recorded can be adjusted using site check readings in conjunction with flow monitoring software. Site check velocity readings were undertaken using a propeller meter. Figure 27 shows the variation between logged and measured velocities for one of the loggers used, along with the required correction factor. It is notable that the accuracy of the logger varies linearly with

[#] MONTEC International Ltd, 5 Pacific Way, Salford, Manchester.
[#] MONTEC International Ltd, 5 Pacific Way, Salford, Manchester.

flow velocity, which in turn highlights the importance of obtaining site calibration data over the range of velocities experienced throughout the DWF pattern.

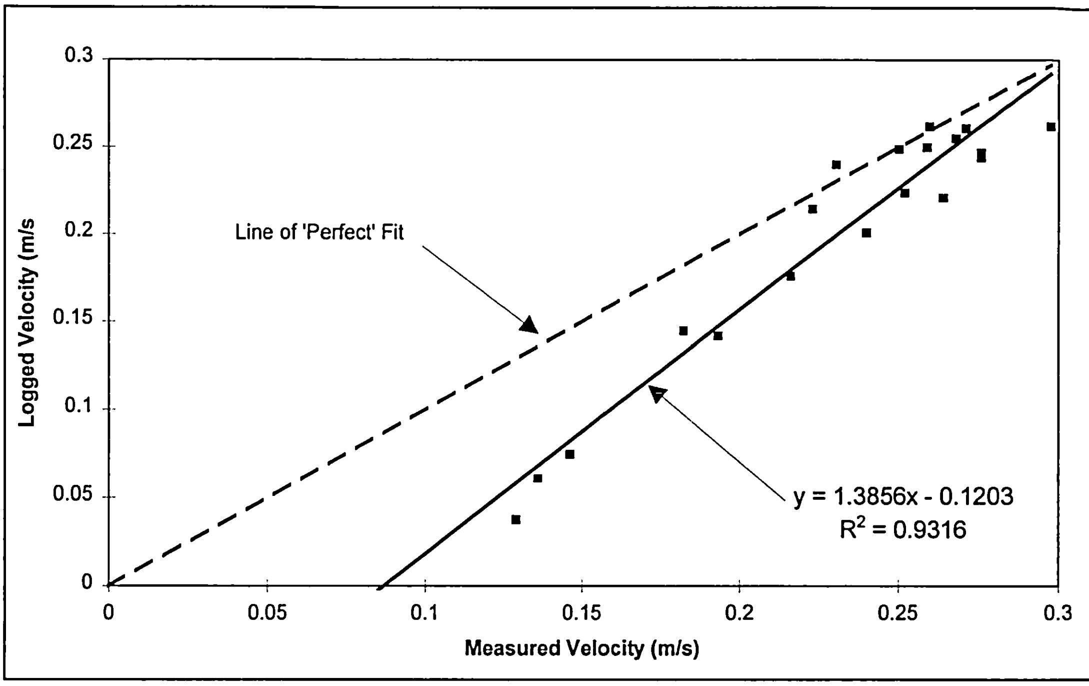


Figure 27 : Sample Logger Calibration Data

5.3 Field Site Details

5.3.1 Study Site 1 - Dens Brae Silt Trap, Trunk Sewer

The first study in this research programme, which was essentially a prototype study, was based in the trunk sewer which serves the 'Dens Brae' catchment, which is to the north-east of the city centre. This sewer carries approximately 1909 m^3/day (668 m^3/day industrial & 1241 m^3/day domestic) from a population of approximately 9500. Most of the domestic population are housed in tenement flats which take up some 70-80% of the land area (Ashley, 1993). The catchment, as a whole, has no history of significant sediment problems. Sedimentation is largely confined to intermittent deposition in manholes, or gross solids in slack gradient collector sewers.

The study site used for data collection consisted of a small silt trap chamber just downstream of an internal overflow. In between the silt trap chamber and the overflow is a penstock which was installed by the operator to facilitate emptying of the silt trap. The upstream pipe is a 1030 × 686 mm brick egg section which is laid at a steep gradient (1:22 ≅ 45.5‰) and connects to the interceptor sewer some distance downstream, following a steep drop.

A test rig had to be constructed, to collect samples at this site. This consisted of a 450mm internal diameter steel pipe which spanned the silt trap supported by 'Acro-Props'. The flow entering the chamber was directed into the steel pipe via a funnel shaped conduit. Towards the end of the pipe, which was 7 m long, an open topped sediment trapping container (700mm long × 200mm wide × 377mm deep) was fitted to the invert of the pipe. The sediment trap was compartmentalised into six equal sized containers, and a cover was fitted to control entry of material into the trap . Suspended solids were sampled via a flexible small diameter (Internal ∅ ≅ 8mm) PVC hose which was weighted before being placed in the flow just upstream of the penstock. The test rig used is illustrated in Figure 28.

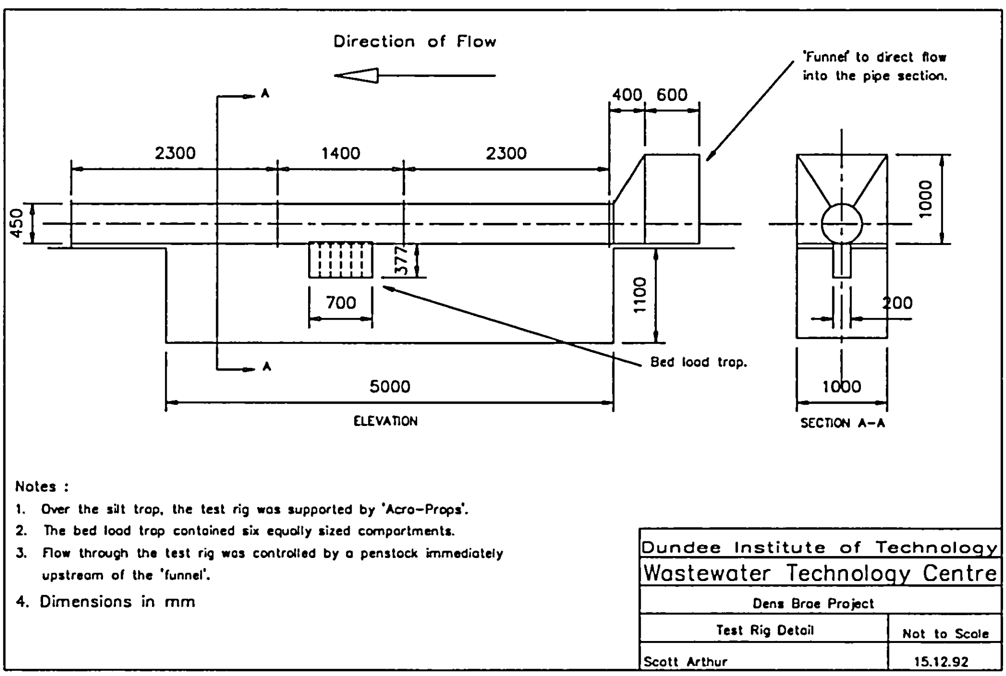


Figure 28 : Study Site 1 test rig

5.3.1.1 Sampling Procedure

The first step in the sampling procedure was to shut off all flow into the silt trap using the penstock, and ensure that all the sediment containers were empty at the start of the test. Following this the cover was placed over the sediment traps and flow was allowed through the test rig. Once the flow had stabilised, the silt traps were uncovered to initiate sampling, sewage sampling was also started simultaneously, using automatic sewage samplers, or manually. Sampling durations varied from 15 minutes to 24 hours. At the end of the sampling procedure, the cover was placed over the sediment traps and the penstock was lowered so that access could be gained to the samples collected. The whole sediment trap was then removed from the invert of the test rig, and a sub sample (~2 litres) was obtained from each of the individual compartments. Samples were collected, using this methodology, from 06.07.92 to 16.09.92 when work was stopped due to completion of the inner ring road in Dundee, which changed the status of the road, under which the test site was situated. However over the duration of Study 1, 9 sets of DWF and 4 sets of storm samples were collected.

5.3.2 Study Site 2 - Samuel's Silt Trap, Interceptor Sewer Site (Head of System)

The test rig installed at Study Site 2 was based an earlier study undertaken at this site (McGregor and Ashley, 1990 and Coghlan, 1995), which is described in section 3.1.2 "Coghlan (1995)".

The sewerage system which serves central Dundee, essentially consists of steep trunk sewers which drain into a large diameter interceptor sewer, which is laid at a shallow gradient. The second site in this study programme is located at the head of the interceptor sewer. The characteristics of the contributing catchments are shown below in Table 26

TABLE 26 : CONTRIBUTING CATCHMENTS FOR STUDY SITE 2

Sub Catchment	Population (× 1000)	Area (ha)	Land Use
Hawkhill	0.280	6.8	T, I & P
Blackness	1.300	20.2	T,H,S & P
Polepark	5.800	159.9	T,H,S,P &I
Guthrie St	0.420	19.3	T & I
Lochee	0.200	14.2	T,I,S & P
City Centre	~5.300	~25	T,S & P
Totals	**13.30**	**245.4**	-

Land Use : T - Tenements / High Rise; I - Light Industry / Commercial; H - Housing; P - Park & Permeable Areas; S - Retail; H - Hospital

The interceptor sewer begins in a chamber where two trunk sewers meet (from the High Street and the Overgate) and the flows mix. At the downstream end of this chamber there is a half gate which may be set to one of two positions, allowing the flow along the interceptor or down into the Dock System. During normal operational conditions the flow passes along the interceptor from the two trunk sewers upstream. However if the flow is sufficient, during significant rainfall events, the gate acts as an internal overflow, passing the excess flow into the Dock System.

Just downstream of the gate is a silt trap which is some 6m long and occupies the full width of the sewer section. At the upstream end of the silt trap the sewer invert is flat for the whole width of the pipe and for a length of 1.5m upstream to aid maintenance of the silt trap.

As the silt trap itself was to be used as a study site, a test rig had to be constructed which spanned the silt trap and met the upstream and downstream sewer section as closely as possible, so that the ambient flow patterns were affected as little as possible. To meet this requirement a timber flume, of a trapezoidal section, was constructed which spanned the entire silt trap. The dimensions of the trapezoidal section were constructed in such a way that they met the geometry of the bottom of the egg section as closely as possible. The flattened invert at the upstream end of the trap was also converted into a trapezoidal section. Although this approach is not necessarily entirely ideal, the results were deemed satisfactory given the tight time and financial restraints of this part of the study. A schematic diagram of the test rig is shown in figure 29.

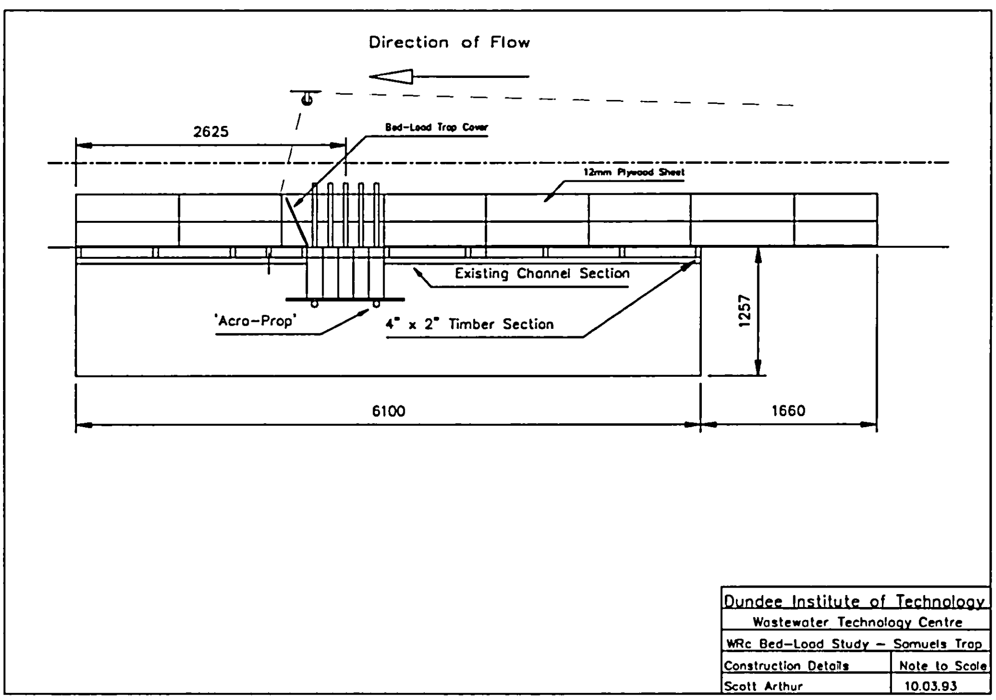


Figure 29 : Study Site 2 test rig

5.3.2.1 Sampling Procedure

Samples of the material moving near the bed were obtained via a sediment trap which was fitted in the invert, towards the downstream end of the flume. The sediment trap was compartmentalised into six separate containers (300mm long × 150mm wide × 300mm deep) and was fitted with a cover to prevent the ingress of material outside the sampling times. Flow velocities and depth were recorded at a single point downstream of the sediment trap, at 2 minute intervals. Sewage samples were obtained at two depths, via semi rigid PVC tubes fixed to the wall of the flume. At this study site it was determined that the optimum time for sampling of the material moving near the bed was 1 hour, as this ensured that only the upstream container was entirely full. Based on this a sampling duration of 48 minutes was selected, as this also allowed the sewage sampler to run a full programme (24 samples) at 2 minute intervals.

Before any samples were obtained from this site, the flow was allowed to pass over the flume for a period of one week, during which time a substantial sediment bed formed along the invert of the flume, and slimes were established on the walls. These materials were physically consistent with the materials found in the upstream and downstream sewer lengths.

The installation of the flume took place between 14.04.93 and 22.04.93. Flow was directed back over this section on 22.04.93. Samples were obtained from the site in the four weeks from 29.04.93 to 27.05.93. During much of the subsequent summer the interceptor was closed for essential maintenance, after which sampling was re-initiated in August when two sets of partial storm data were obtained, before the flume was removed on 18.01.94.

5.3.3 Study Site 3 - Constable Street Silt Trap, Downstream Interceptor Sewer
In terms of the investment of time, finance and technical competence Study 1 and Study 2 were largely prototypes, which were used to gain experience for the work undertaken as part of Study 3.

Approximately 665m downstream of the site utilised in Study 2 is a second silt trap, which was used as a data collection site in Study 3. Similarly to Samuel's silt trap this silt trap takes up the whole width of the sewer and is some 6.13m long and 1.233m deep (12.28m^3). The sewer at this location is an egg section (1780mm × 1625mm wide) and has an invert gradient of 1:~1750 (~0.57‰). For the purposes of maintenance this silt trap has half gates fitted at each end which, when closed across both ends of the trap, divert the flow through a bypass and around the immediate length of the silt trap. Good access is allowed to the site via 5 manholes over a length of around 15m. The test rig is illustrated schematically in Figure 30.

Fifteen metres upstream of the silt trap used in Study 3, a trunk sewer (which drains the Dens Brae Sub-Catchment) passes under the interceptor sewer at a angle of 90°. During quite substantial rainfall events the trunk sewer spills into the interceptor sewer via a double internal overflow. Much more commonly, however, the interceptor sewer will spill into the trunk sewer via a second overflow, just downstream of the spill from the trunk sewer CSO, during moderate rainfall events. This second case may have been exacerbated by the presence of the test rig.

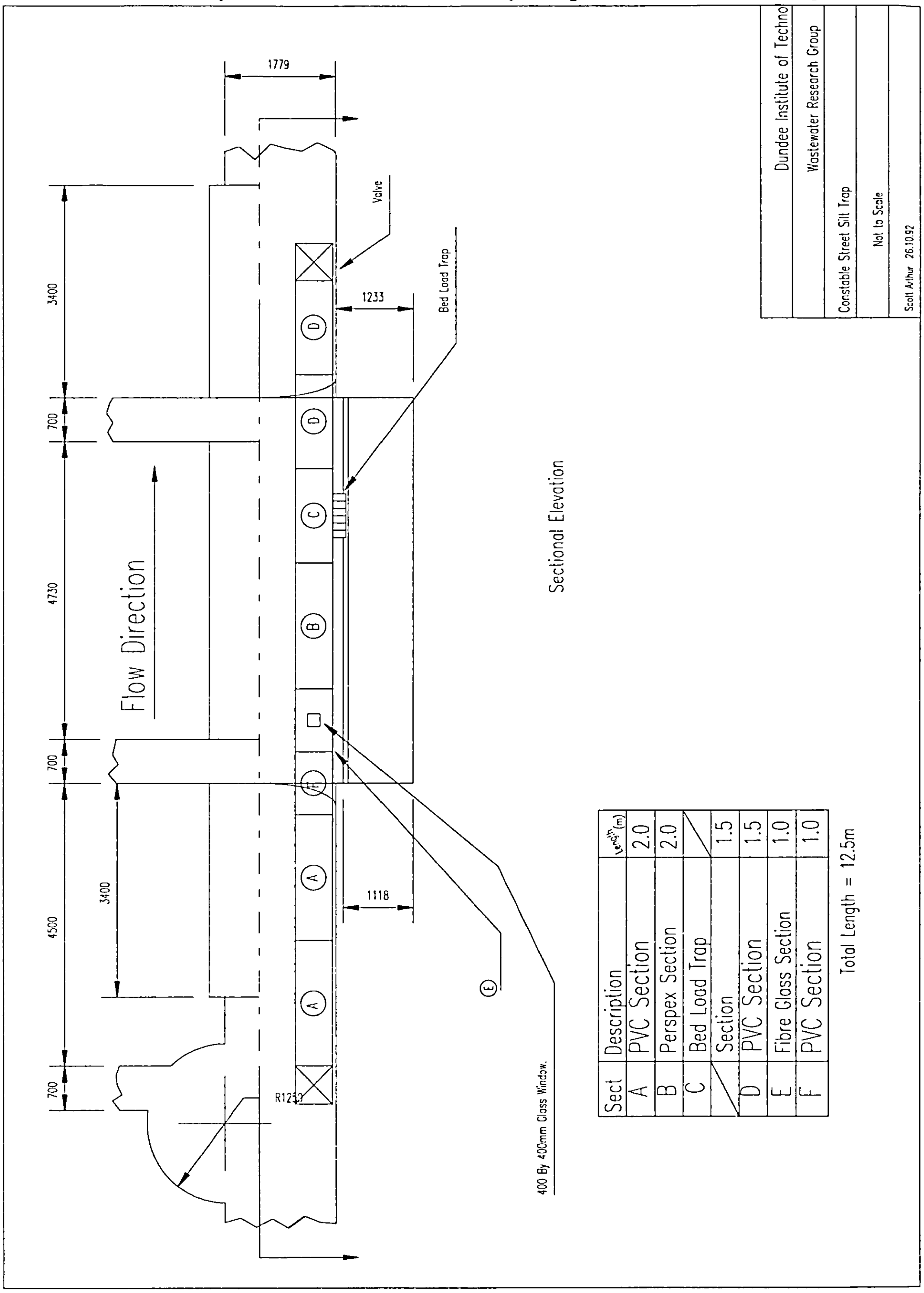


Figure 30 : Study Site 3 test rig

Between the sites used in Study 2 and Study 3 the sewer length is affected by considerable amounts of sediment, particularly in the 400m immediately downstream of Samuels silt trap (Figure 31). The physical and chemical characteristics of the sediments vary considerably spatially from fine organic slurries, to substantial amounts of rubble, to well consolidated and cemented sediments. Along this length substantial amounts of material can be identified from each of the WRc sediment classes (Crabtree, 1987). The particle size distribution for sediment samples obtained at 100 m intervals between Study sites 2 and 3 is illustrated in Figure 32.

Although the two Interceptor sewer study sites are less than 700m apart there are significant differences in the contributing catchments during DWF. The main additional inputs being from the Hilltown, and Constitution Street sub-catchments, as illustrated below in Table 27.

TABLE 27 : CONTRIBUTING CATCHMENTS FOR STUDY SITE 3

Sub Catchment	Population (× 1000)	Area (ha)	Land Use
Hawkhill	0.280	6.8	T, I & P
Blackness	1.300	20.2	T,H,S & P
Polepark	5.800	159.9	T,H,S,P &I
Guthrie St	0.420	19.3	T & I
Constitution Rd.	2.900	64.6	T,H,I,S,P
Hilltown	1.900	30.3	T,H,I,P
Lochee	0.200	14.2	T,I,S & P
City Centre	~5.300	~25	T,S & P
Totals	**18.1**	**340.3**	-

Land Use : T - Tenements / High Rise; I - Light Industry / Commercial; H - Housing; P - Park & Permeable Areas; S - Retail; H - Hospital

At this site the test rig consisted of a 14m long 560mm internal diameter pipe, made from various materials, which spanned the silt trap (see plates 1 & 2). Directly over the silt trap, the test rig was supported on a false steel floor which was fixed to the walls of the silt trap. At each end of the silt trap, around the test rig, temporary concrete walls were constructed, which were high enough to exclude flows during DWF and small rainfall events (see plates 3 & 4). The presence of these walls provided a 'dry' working area in which tests could be undertaken and data collection undertaken in comparative comfort.

Flow through the test rig was controlled by two specially fabricated PVC-U slide valves at each end of the pipe. Flow which did not pass through the pipe (~20% during DWF conditions) was directed around the bypass. The remainder of the test rig was modular in construction, being largely based on specially modified sections of 24" external diameter PVC-U Class C water supply pipe. Sections were also constructed from clear PVC and acrylic to facilitate flow visualisation (see plates 5 & 6). An additional section was installed which had a glass viewing window for use with a Laser Doppler Anemometer (LDA) unit, which was to be used for velocity measurement in 3 dimensions near the bed.

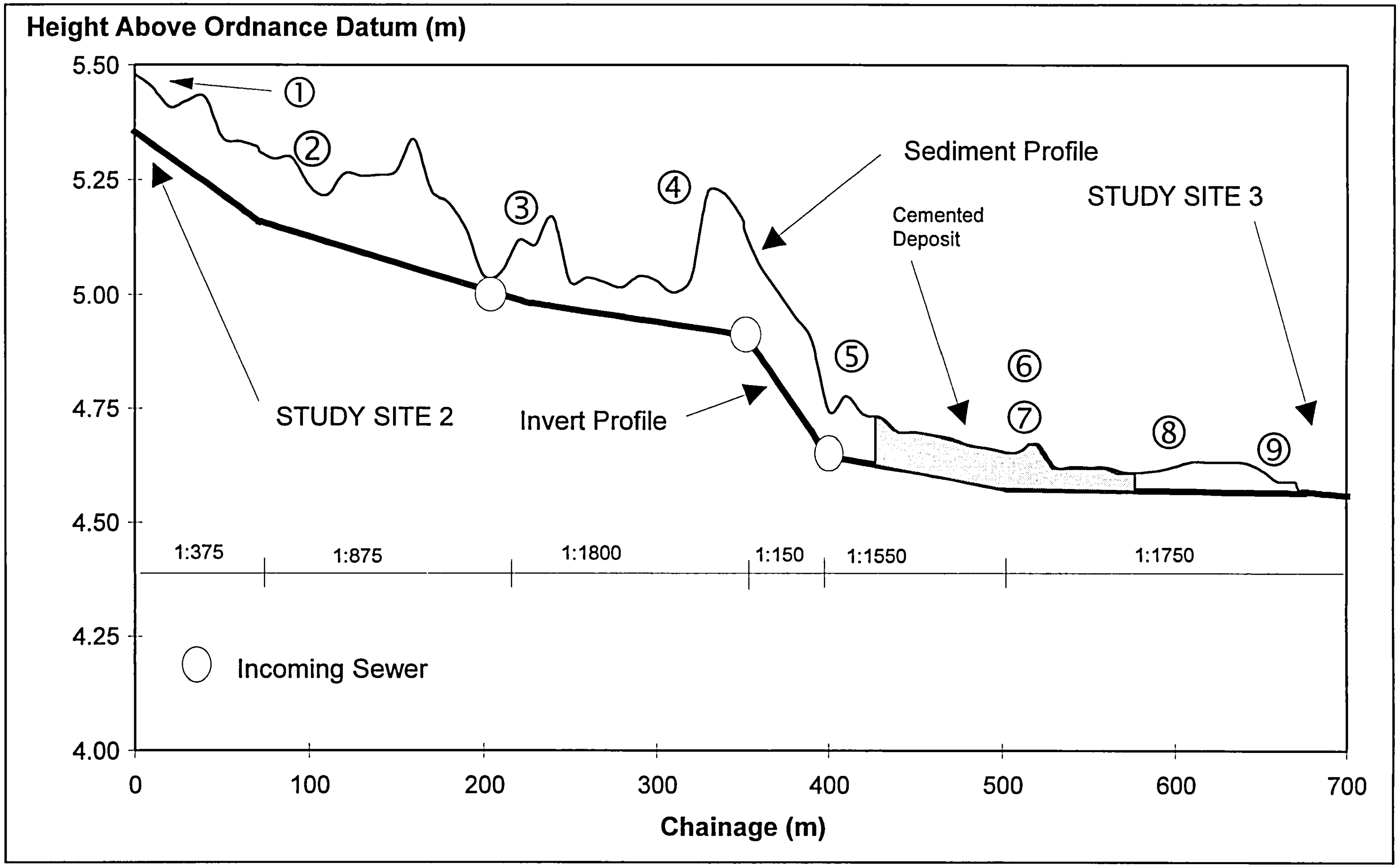


Figure 31 : Sediment Depth variation between Study Sites 2 & 3 (23.08.95)

⓪ - Sediment sample retrieved

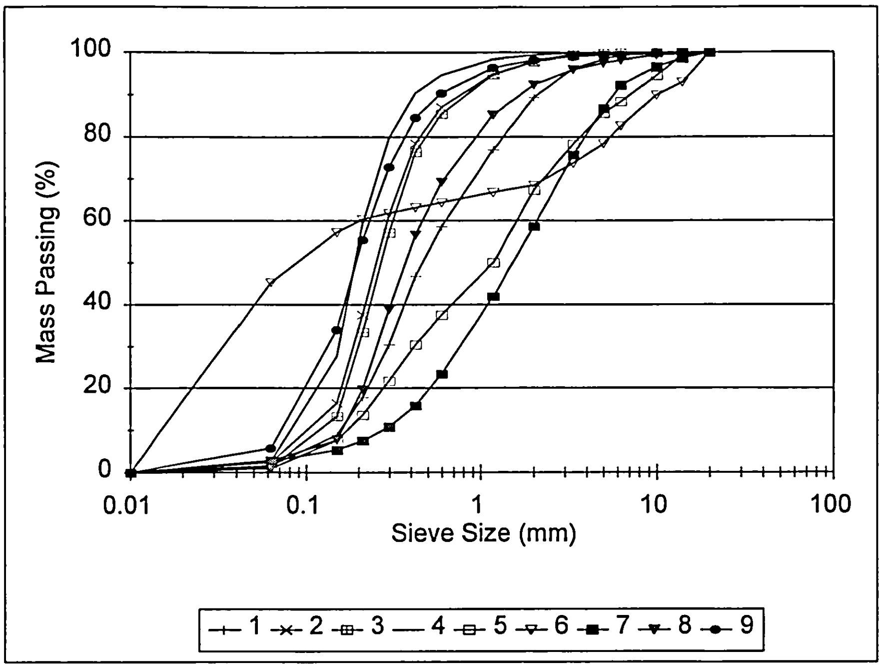


Figure 32 : Sediment PSD between Study Sites 2 & 3 (23.08.95)

5.3.3.1 Test Procedure and Instrumentation

When the test rig was first installed the primary aim was to study the development of a sediment bed along the entire length of the test section so that sediment transport over a deposited bed, as well as erosion tests, could be carried out. However it was found that the velocities developing inside the test section were excessive (>1m/s during DWF conditions). To reduce the ambient velocity conditions, and thus encourage a sediment bed, a weir was constructed 5m downstream of the test rig. The weir had the effect of increasing the depth and reducing the velocity of the flow, but did not result in the development of a sediment bed. Further attempts were made to encourage sediment deposition, these are listed below;

- Placing erratics (large boulders and bricks) along the invert.
- Moving sediment from other areas of the sewer network to just upstream of the test section.
- Moving sediment from other areas of the sewer network and distribute it along the invert of the test section.
- Placing crushed bricks, crushed concrete, and 20mm (down) aggregate along the invert.
- Blocking the bottom portion of the outlet.

None of these methods resulted in a sediment bed which would remain in place even during DWF. As no sediment bed would form, or could apparently be encouraged to do so, it was decided to study sediment transport without a deposited bed.

To sample the material moving near the bed of the sewer two methods were employed, these are briefly described below;

1. Sediment traps fitted in the invert

Similarly to Study 1 and Study 2, material moving near the bed was sampled via a compartmentalised sediment trap fitted to the invert of the test section, toward the downstream end. At this site the trap was fitted with a removable cover which was used to initiate sampling (see plates 7, 8 & 9).

2. Small bore rigid sampling tubes

Samples of the material moving near the bed were also obtained, with some degree of success, using EPIC 1011 wastewater samplers in conjunction with a rigid 10mm internal diameter sampling tube, placed directly on the invert (see plates 10 & 11). At the outset it was recognised that this method is very selective in the size of material obtained (i.e. <10mm).

Sewage samples were obtained at this site via rigid PVC or copper tubing, at 1, 2 3 or 4 known depths, connected to EPIC 1011 wastewater samplers. Velocity and depth were recorded at 1 minute intervals throughout the study at two points in the test rig; towards the upstream and downstream ends of the pipe. Towards the end of the study a third logger was installed upstream of the test rig to monitor the hydraulic conditions.

5.5 Conclusions

Three, non-concurrent, field sites were established in the Dundee combined sewer network to monitor solids in transport in general, and the material in transport near the bed in particular. The data collection methods employed at each site were similar, thus ensuring that direct comparisons could be made between the data collected at each of the study sites.

The data collection methodology proposed was based on site characteristics, ambient hydraulic conditions and the nature of the material in transport near the bed of each of the proposed study sites.

Chapter 6 : Study Results

6.1 Introduction

This chapter gives details of the observations made at each of the data collection sites and gives information on the results. The chapter begins by making comparisons between the material sampled at each of the sites, and then considers specific findings and observations.

In Chapter 5, an overview was given of the Dundee sewerage system, the data collection procedures, and each of the study sites.

Study Site 1 utilised a 450mm steel pipe which was installed in a silt-trap chamber which led on from a 1030 by 686mm brick egg-shaped sewer in the Dens Road area of Dundee. The steel sewer was fabricated with six traps in the invert of the pipe which were used to collect samples of the material moving at the bed. Sewage flows into the chamber were controlled via a penstock. The catchment upstream of the chamber is very steep, with the inlet sewer having a gradient of 1:22, and the contributing population being 10340. Sedimentation in the catchment is minimal, being confined largely to intermittent gross solids in the slacker gradient collector sewers.

Study Site 2 was based in the centre of Dundee, at the head of the interceptor. Just upstream of the site is a large chamber where the flows from two trunk sewers mix and enter the interceptor system. The gradient of the sewer in this area is less than 1:1000, and there is a contributing population of 14700 (1990). The rig used to collect samples consisted of a wooden trapezoidal flume spanning a silt trap. Near bed solids samples were obtained via a trap in the invert which was compartmentalised into five rectangular containers. At this site it was found that a sediment bed rapidly established itself along the entire length of the test section, as well as both upstream and downstream, this being primarily due to the stilling effect of the upstream connection.

Study 3 was based in a silt trap approximately 700m downstream of that used in Study 2. At this site, approximately 60-70% of the flow passing through the interceptor (1780 × 1625 egg section) was carried by a 15 m long 560 mm internal diameter prosthetic sewer which spans a silt trap at the site. As with the test rig used in Study 1, no permanent sediment bed formed at this site. Just downstream of the test section a small weir was constructed, in an attempt to control the velocity conditions. As with the Studies 1 and 2, near bed solids samples were collected via a compartmentalised open topped container fixed to the invert of the pipe. Sewage samples were collected simultaneously at a single or two depths. In conjunction with the sewage and sediment sampling programme, gross solids have also been collected in an attempt to gain an estimate of the rate at which they are transported through the system.

The work undertaken at the three field sites over the duration of this study generated a considerable amount of data relating to the physical and pollutant characteristics of the solids transported in sewers, as well as hydraulic data. The data collected at Study Sites 1, 2 and 3 are summarised in Tables 28, 29 and 30 respectively. The tables highlight the broad range of conditions under which data were collected.

TABLE 28 : STUDY SITE 1 DWF SAMPLE SUMMARY

Sample No.	1	2	3	4	5
Date	06.07.92	15.07.92	21.07.92	27.07.92	29.07.92
Rain Depth	DWF	DWF	8mm	DWF	DWF
ADWP	60 Hrs	86 Hrs	44 Hrs	17 Hrs	4hrs
Start Time (BST)	14:30	14:10	14:05	10:20	14:00
Sampling Duration	15 min	15 min	30 min	1 hr	24 hrs
Flow Data	Intact	Intact	Intact	Intact	Intact
AVG Velocity (m/s)	0.57	0.68	1.08	0.53	0.54
Depth (m)	0.193	0.197	0.255	0.200	0.200
Total Flow (m^3)	36.7	41.8	94.5	108.0	3200
Invert Traps Containing Material	6/6	2/6	6/6	6/6	6/6
Sewage Samples	✓	✓	✓	✓	✓

Sample No.	6	7	8	9
Date	12.08.92	24.08.92	09.09.92	16.09.92
Rain Depth	DWF	7mm	1 mm	2mm
ADWP	9 Hrs	2 Days	3 Days	2 Days
Start Time (BST)	14:00	14:00	14:20	14:00
Sampling Duration	24 hrs	24 hrs	24 hrs	24 hrs
Flow Data	Intact	Intact	Intact	Intact
AVG Velocity (m/s)	0.64	0.64	0.69	0.58
Depth (m)	200	220	252	241
Total Flow (m^3)	2873	5305	5159	5380
Invert Traps Containing Material	6/6	6/6	6/6	6/6
Sewage Samples	✗	✗	✓	✓

TABLE 29 : STUDY SITE 2 SAMPLE SUMMARY

Sample No.	1	2	3	4	5
Date	29.04.93	13.05.93	19.05.93	25.05.93	27.05.93
ADWP	4 days	5 days	30 hrs	5 days	7 days
Time (GMT)	13:06-13:54	05:41-06:29	06:53-08:05	13:51-14:49	09:40-10:30
Duration	48 min	48 min	72 min	48 min	48 min
AVG Velocity (m/s)	0.40	0.34	0.40	0.44	0.46
Total Flow (m^3)	244.6	192.1	257.9	235.6	262.2
Depth (m)	0.352	0.319	0.351	0.316	0.326
Invert Traps Containing Material	5/5	2/5	5/5	5/5	5/5
Deposited Sediment Sample	✗	✗	✓	✓	✓
Sewage Samples	✓	✓	✓	✓	✓

TABLE 30 : STUDY SITE 3 DWF SAMPLE SUMMARY

Data Set	1	2	3	4	5	6
Date	01.03.95	08.03.95	15.03.95	22.03.95	29.03.95	06.04.95
Start (GMT)	10:40	11:32	10:56	12:39	10:07	09:40
Finish (GMT)	11:28	12:18	11:44	13:27	10:55	10:28
Duration (mins)	48	48	48	48	48	48
Sewage	×	✓	✓	✓	✓	✓
Invert Traps Containing Material	6/6	6/6	6/6	6/6	6/6	6/6
Avg Velocity (m/s)	0.209	0.313	0.325	0.268	0.263	0.244
AVG Depth (m)	0.497	0.526	0.546	0.527	0.544	0.528
AVG Flow (m^3/s)	0.048	0.075	0.079	0.065	0.064	0.058
Total Flow (m3)	141.8	215.4	228.7	185.8	184.9	168.4
Bed Shear (N/m^2)	0.0936	0.2040	0.2359	0.1564	0.1648	0.1181
ADWP (h)	17.5	27.0	103.0	114.8	64.7	25.0

Data Set	7	8	9	10	11
Date	12.04.95	18.04.95	26.04.95	03.05.95	17.05.95 a
Start (GMT)	09:26	10:41	10:17	09:47	02:48
Finish (GMT)	10:14	11:29	11:05	10:35	04:48
Duration (mins)	48	48	48	48	120
Sewage	✓	×	✓	✓	✓
Invert Traps Containing Material	6/6	6/6	6/6	6/6	6/6
Avg Velocity (m/s)	0.258	0.265	0.275	0.271	0.125
AVG Depth (m)	0.522	0.512	0.511	0.518	0.455
AVG Flow (m^3/s)	0.061	0.063	0.065	0.065	0.027
Total Flow (m3)	176.8	183.9	186.1	185.8	191.8
Bed Shear (N/m^2)	0.1309	0.1362	0.1485	0.1416	0.0325
ADWP (h)	66.0	15.6	76.1	89.6	36.9

Data Set	12	13	14	15	16
Date	17.05.95b	13.06.95a	13.06.95b	20.06.95a	20.06.95b
Start (GMT)	05:45	14:24	15:50	05:53	07:36
Finish (GMT)	06:33	15:12	16:44	06:41	08:24
Duration (mins)	48	48	54	48	48
Sewage	✓	✓	✓	✓	✓
Invert Traps Containing Material	6/6	6/6	6/6	3/6	6/6
Avg Velocity (m/s)	0.166	0.230	0.238	0.214	0.274
AVG Depth (m)	0.472	0.506	0.502	0.483	0.522
AVG Flow (m^3/s)	0.036	0.054	0.055	0.048	0.064
Total Flow (m3)	105.1	154.8	179.8	139.3	188.4
Bed Shear (N/m^2)	0.0635	0.1268	0.1360	0.1096	0.1924
ADWP (h)	111.2	162.1	164.0	4.2	6.0

TABLE 30 : STUDY SITE 3 DWF SAMPLE SUMMARY (CONTINUED)

Data Set	17	18	19	20	21
Date	27.06.95	17.07.95a	17.07.95b	26.07.95	27.07.95
Start (GMT)	12:40	16:48	18:12	22:03	00:29
Finish (GMT)	13:28	17:36	20:12	00:03	02:29
Duration (mins)	48	48	120	120	120
Sewage	×	✓	✓	✓	✓
Invert Traps Containing Material	6/6	2/6	6/6	6/6	6/6
Avg Velocity (m/s)	0.225	0.211	0.204	0.190	0.150
AVG Depth (m)	0.499	0.482	0.479	0.473	0.447
AVG Flow (m^3/s)	0.052	0.048	0.046	0.042	0.032
Total Flow (m3)	150.4	136.9	329.3	120.7	91.3
Bed Shear (N/m^2)	0.1247	0.0917	0.0861	0.0686	0.0454
ADWP (h)	178.1	47.6	49.4	88.7	91.1

These data represent the most comprehensive range of data regarding near bed solids collected in the UK, or elsewhere, to date with regards to information relating both physical and pollutant characteristics.

6.2 Hydraulic Conditions

The most important factors which affect the nature of the material in transport in sewers, rivers, streams etc. are the ambient hydraulic conditions. As discussed in Chapter 5; "Catchment Overview and Data Collection Procedures", the sites were selected in such a way as to ensure a wide range of hydraulic conditions. Additionally, at each site hydraulic conditions were continuously varying, due to the varying inputs to the system. The average DWF hydraulic conditions at each of the study sites are summarised in Table 31, and illustrated in Figures 33, 34 and 35. The hydraulic data available for Study Site 1 is not as detailed as that from Study Site 2 and 3, and as such the ranges expressed in this section for this site may only be indicative

TABLE 31 : STUDY SITES 1, 2 & 3 AMBIENT DWF HYDRAULIC CONDITIONS OVER A 24 HOUR PERIOD

	Velocity (m/s)		Depth (m)		Flow (l/s)		Boundary Shear (N/m^2)	
	min.	max.	min.	max.	min.	max.	min.	max.
Study 1	0.410	0.770	0.159	0.244	20.8	66.5	0.504	1.779
Study 2	0.302	0.457	0.304	0.363	53.8	106.4	0.205	0.469
Study 3	0.090	0.290	0.441	0.518	19.0	69.0	0.017	0.183

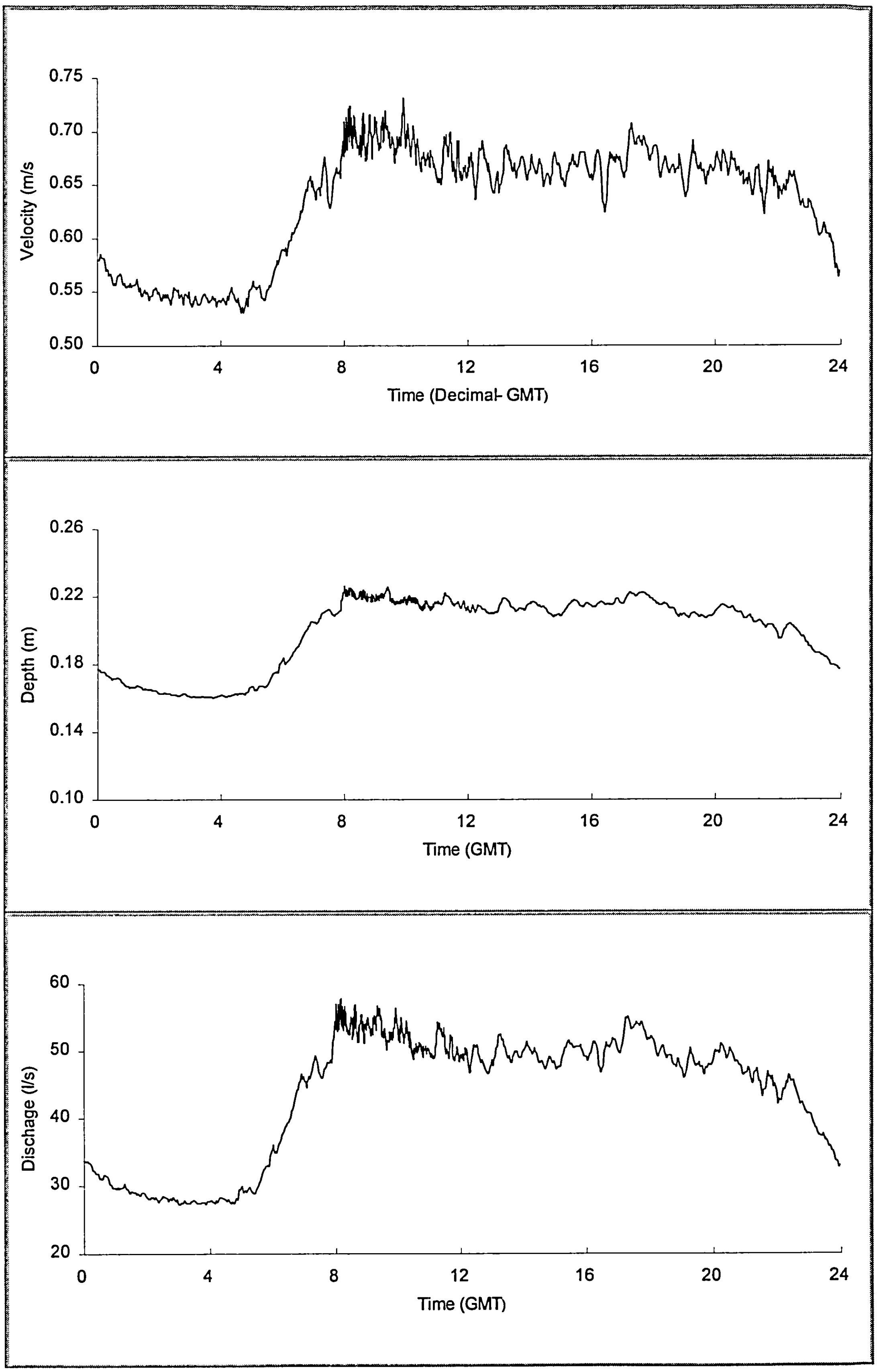


Figure 33 : DWF hydraulic conditions - Study Site 1

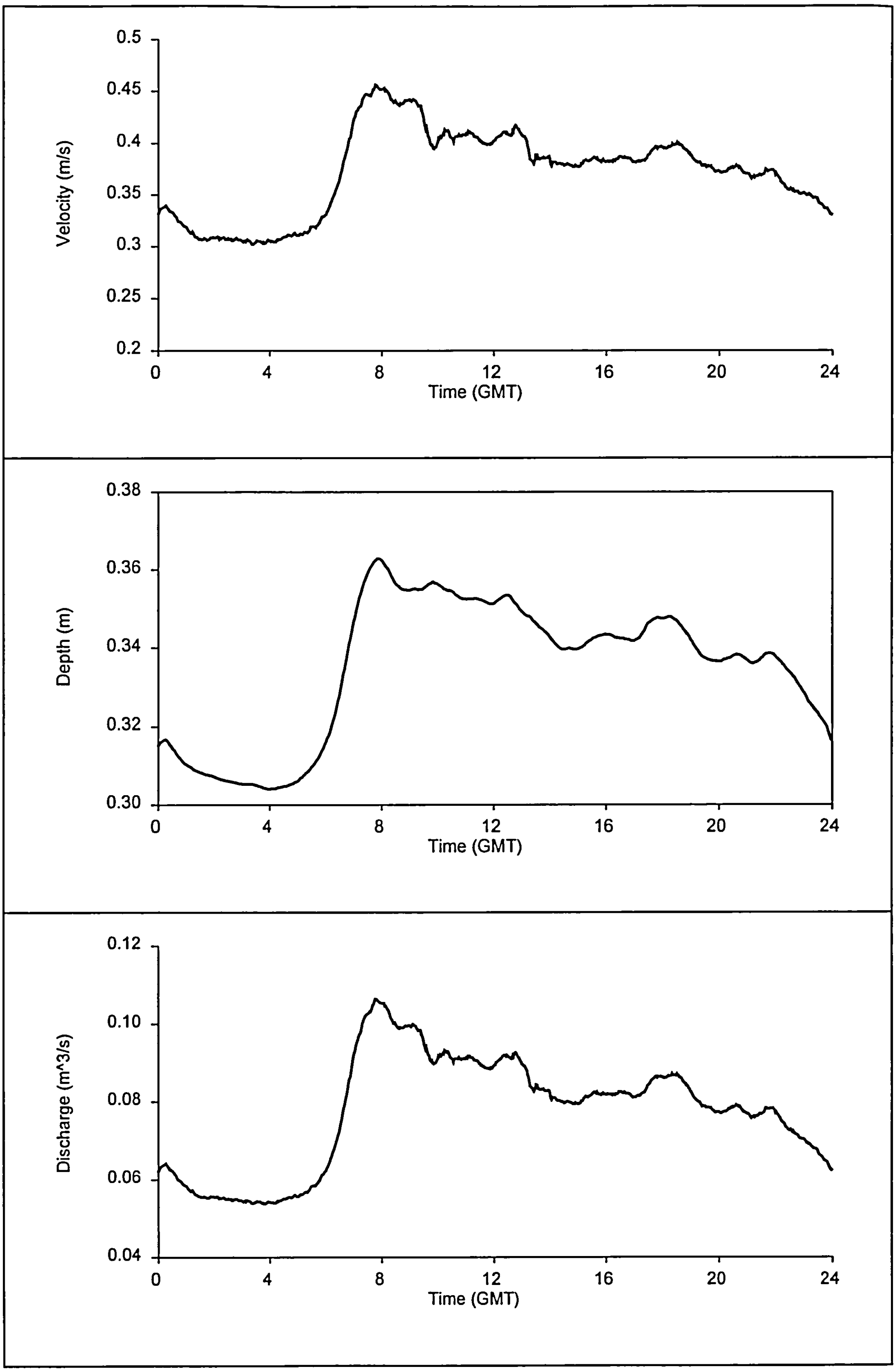


Figure 34 : DWF hydraulic conditions - Study Site 2

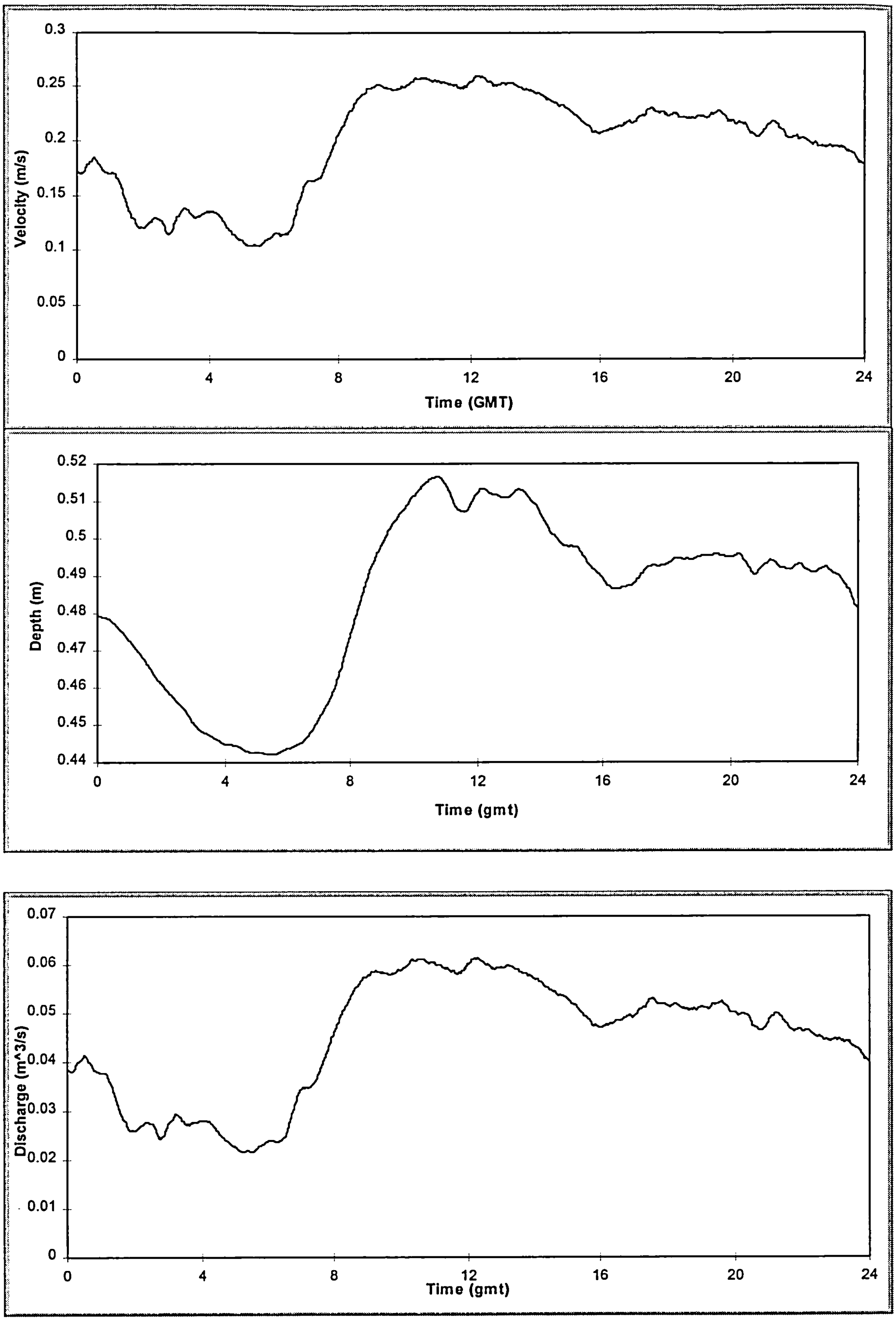


Figure 35 : DWF hydraulic conditions - Study Site 3#

Little variation is observed in the depth profile observed at Study Site 3 due to the presence of the weir described in section 5.3.3 'Study Site 3'.

In addition to the changes in the flow conditions throughout an average DWF period there are also considerable variations from day to day, especially at weekends due to the different social activities in the catchment. Additionally, changes in the DWF hydrograph are also observed at the transition between British Summer Time (BST) and Greenwich Mean Time (GMT) due to the changes in the daily habits of the catchment population. To avoid these variations data were only collected on Tuesdays, Wednesdays and Thursdays.

6.3 Sampled Solids Characteristics

6.3.1 Near Bed Solids (NBS)

Each individual sample of near bed solids material retrieved from the three study sites was tested, where possible, for each of the following.

Particle Size Distribution

Primarily undertaken on the inorganic fraction of the material in transport, although observational analysis was undertaken on organics. The test undertaken on the mineral fraction was in accordance with BS1377 (BSI, 1975).

Bulk/Dry Density

The bulk destiny of each sample retrieved was determined, to give an estimation of the characteristics of particles in transport. Specific gravities were determined solely on the basis of the bulk density. The dry density, which is used in geotechnics to estimate the degree of compaction in soils (Craig, 1987 & Smith, 1990), was used as it gives a value for the mass of (dry) solids per unit volume of sample. This is necessary as when dealing with material with very high moisture contents (>1000%), since when the moisture content gradually increases the bulk density approaches that of water asymptotically. Dry density is often used by researchers in alluvial sediment transport, notably Mehta & Partheniades (1975).

Moisture Content

Moisture contents were determined by drying the sample in a oven at 105°C. The moisture content is expressed as a percentage ratio of water to dry solids by weight.

Inorganic/Organic Fraction.

The organic fraction of the near bed solids retrieved from the field was removed by furnacing the dry sample at 550°C. The organic content is expressed as a percentage of the total dry mass.

Biochemical Pollutant Characteristics

Each sample, where possible, was tested for BOD_5, COD and Ammonia concentrations.

Settling Velocity

Where possible, each sample was tested for settling velocity.

It is not the purpose of this project to discuss the merits of the methodologies employed in undertaking each of the tests outlined above. All test were undertaken in accordance with accepted methodologies (Crabtree & Forster, 1989) in a quality assured laboratory environment by experienced biology and chemistry postgraduate level scientists employed at WWTC.

Unless otherwise stated, all properties quoted refer to the averages for the material collected in all of the invert containers. However, there were slight variations in the nature of the material found in individual traps. The upstream traps, which filled quickest (see plate 12), typically contained material of higher particle size which also had slightly higher density.

6.3.1.1 Physical Characteristics

As, in principle, the same sample collection methodology was employed at each of the study sites it is possible to make direct comparisons between the material collected at each of the sites.

TABLE 32 : SUMMARY OF THE NEAR BED SOLIDS MATERIAL COLLECTED AT STUDY SITE 1

	06.07.92	15.07.92	21.07.92	27.07.92	29.07.92	12.08.92	24.08.92	09.09.92	16.09.92
Bulk Density (kg/m^3)	1474.8	1513.0	1733.9	1521.0	1404.5	1303.4	1776.2	1539.5	1285.9
Solids (%)	86.1	65.3	84.5	76.3	74.4	49.0	77.1	41.8	41.6
MC (%)	16.4	55.4	18.7	33.5	37.1	109.5	30.0	184.3	167.8
Volatile Solids (%)	1.8	1.6	1.6	1.4	5.1	28.6	4.3	19.5	28.6
Dry Density (kg/m^3)	1268.4	989.0	1455.5	1158.0	1042.7	644.2	1370.6	679.2	578.6

TABLE 33 : SUMMARY OF THE NEAR BED SOLIDS MATERIAL COLLECTED AT STUDY SITE 2

	29.04.93	13.05.93	19.05.93	25.05.93	27.05.93
Bulk Density (kg/m^3)	1097.7	1134.7	1158.4	1032.2	1038.2
Solids (%)	15.1	19.2	24.3	18.9	16.2
Moisture Content (%)	583.9	422.6	335.4	492.2	531.0
Volatile Solids (%)	59.9	53.8	31.8	68.1	57.7
Dry Density (kg/m^3)	160.5	217.3	266.1	174.3	164.5

TABLE 34 : SUMMARY OF THE MATERIAL COLLECTED AT STUDY SITE 3

Data Set No.	1	2	3	4	5	6	7
Date	01.03.95	08.03.95	15.03.95	22.03.95	29.03.95	06.04.95	12.04.95
Solids (%)	8.0	8.2	9.9	11.2	10.1	10.2	9.4
Moisture Content (%)	1200.0	1124.0	966.7	799.7	901.8	969.7	980.7
Volatile Solids (%)	55.6	73.7	81.9	75.2	82.5	83.5	81.3
Bulk Density (kg/m^3)	1029.4	982.7	1002.8	980.6	993.3	1018.1	1003.7
Specific Gravity	1.03	0.98	1.00	0.98	0.99	1.02	1.00
Dry Density (kg/m^3)	79.2	80.3	94.0	109.0	99.1	95.2	92.9
Bulk Volume (l)	11.2	10.9	7 .3	10.0	13.0	12.8	9.1
Bulk Weight (kg)	11.5	10.7	7.3	9.8	12.9	13.1	9.2
Total Dry Weight (g)	890.0	902.3	766.5	1137.7	1322.0	1314.3	871.1
Total Inorganic Weight (g)	397.2	236.0	133.3	286.7	231.1	207.2	161.1
Total Organic Weight (g)	492.8	666.3	633.1	851.1	1090.8	1107.1	710.0

Data Set No.	8	9	10	11	12	13	14
Date	18.04.95	26.04.95	03.05.95	17.05.95a	17.05.95b	13.06.95a	13.06.95b
Solids (%)	9.0	8.4	7.0	3.6	6.3	5.5	5.5
Moisture Content (%)	1025.6	1105.4	1382.3	3759.6	1536.0	1900.3	1900.3
Volatile Solids (%)	72.6	78.3	76.6	67.9	87.6	63.0	63.0
Bulk Density (kg/m^3)	1010.2	995.7	1000.4	1013.4	970.7	1108.2	1002.4
Specific Gravity	1.01	1.00	1.00	1.01	0.97	1.11	1.00
Dry Density (kg/m^3)	89.7	82.6	67.5	26.3	59.3	55.4	50.1
Bulk Volume (l)	9.0	9.0	4.9	9.0	6.2	8.4	8.4
Bulk Weight (kg)	9.1	8.9	5.0	9.1	6.0	9.2	8.5
Total Dry Weight (g)	808.7	766.6	366.9	311.8	404.7	464.3	464.3
Total Inorganic Weight (g)	222.2	169.1	80.2	81.6	55.4	169.2	169.2
Total Organic Weight (g)	586.5	597.4	286.7	230.2	349.2	295.0	295.0

Data Set No.	15	16	17	18	19	20	21
Date	20.06.95a	20.06.95b	27.06.95	17.07.95a	17.07.95b	26.07.95	27.07.95
Solids (%)	8.7	13.3	11.2	6.5	6.9	7.9	4.4
Moisture Content (%)	1049.5	708.9	814.3	1611.4	1361.3	1244.7	2416.6
Volatile Solids (%)	80.0	86.5	77.7	84.0	77.6	84.3	91.2
Bulk Density (kg/m^3)	981.3	991.1	1005.6	996.1	1008	984.5	980.4
Specific Gravity	0.98	0.99	1.01	1.00	1.01	1.0	1.0
Dry Density (kg/m^3)	85.4	122.5	110.0	58.2	69.0	73.2	39.0
Bulk Volume (l)	2.7	10.0	11.9	2.7	6.234	9.7	4.6
Bulk Weight (kg)	2.7	10.0	12.0	2.6	6.296	9.5	4.5
Total Dry Weight (g)	244.1	1408.9	1346.1	146.3	439	785.2	219.6
Total Inorganic Weight (g)	52.6	206.5	304.1	22.9	114	115.7	19.4
Total Organic Weight (g)	191.4	1202.4	1042.1	123.4	325	669.5	200.2

A summary of the material characteristics for each of the study sites is given in Tables 32, 33 and 34, and the ranges for Study Site 3 are given in Table 35. Full details of each individual sample of the material obtained moving at the bed at each of the study sites are given in Appendix A.

As the tables illustrate, there are considerable differences in the nature of the material moving at the bed at each of the sites. The material collected as Study Site 1 being characterised, broadly, as a predominately inorganic material of relatively high average density (average 1505.8 kg/m^3) and particle size. Conversely, the material collected at Study Site 3 was observed to be highly organic (up to an average of 91.2%), with only a very fine inorganic fraction on average. The data sets collected at study site 2 are consistent with that obtained by Coghlan (1995) at the same site.

TABLE 35 : RANGE OF THE MATERIAL COLLECTED AT STUDY SITE 3

	AVG	S.D.	MIN	MAX
	1 - 21	1 - 21	1 - 21	1 - 21
Solids (%)	8.2	2.3	3.6	13.3
Moisture Content (%)	1350.3	667.0	708.9	3759.6
Volatile Solids (%)	77.8	8.2	55.6	91.2
Bulk Density (kg/m^3)	997.5	14.0	970.7	1029.4
Specific Gravity	1.0	0.0	1.0	1.0
Dry Density (kg/m^3)	78.3	23.5	26.3	122.5
Bulk Volume (l)	8.5	2.9	2.7	13.0
Bulk Weight (kg)	8.5	3.0	2.6	13.1
Total Dry Weight (g)	740.2	390.3	146.3	1408.9
Total Inorganic Weight (g)	163.7	95.3	19.4	397.2
Total Organic Weight (g)	576.6	322.4	123.4	1202.4

6.3.1.1.1 Particle Size Distribution

Particle size distribution analyses were carried out on each of the near bed solids samples obtained from the three study sites. The analysis was based on the standard geotechnical test (BS 1377) for particles in the range 63μm and 20.0mm. This test was developed for discrete, principally inorganic, particles. The different size fractions being separated by mechanical sieving. Due to the nature of the test only the inorganic fraction of the material could be tested with any degree of accuracy, as inorganic particles would quickly break down. The organic fraction was removed by furnacing (550°C) a sub-sample (500 - 1000ml, where possible). For the samples obtained from Study Sites 1 & 2 this proved adequate, however, due to the high organic content of the samples obtained from Study Site 3 this methodology led to possible inaccuracies. This principally being due to the observation that the furnaced samples tested were primarily composed of the ashed remnants of the organic fraction. However, due to the high organic levels in the samples obtained from Study Site 3, the particle size distribution of the inorganic particles was less important than that at Study Sites 1 and 2.

A summary of the range of particle size distributions observed at each of the data collection sites is illustrated in Figure 36, and full details of the test carried out on each sample are given in Appendix B.

Although the particle size distribution of the inorganic fraction of the material in transport is affected by upstream conditions and sediment supply rates, the difference in the inorganic particle sizes between the sites can also be attributed to the differences in ambient velocity conditions. The data indicate that the site with higher velocity conditions has the coarsest particles in transport near the bed, and vice versa.

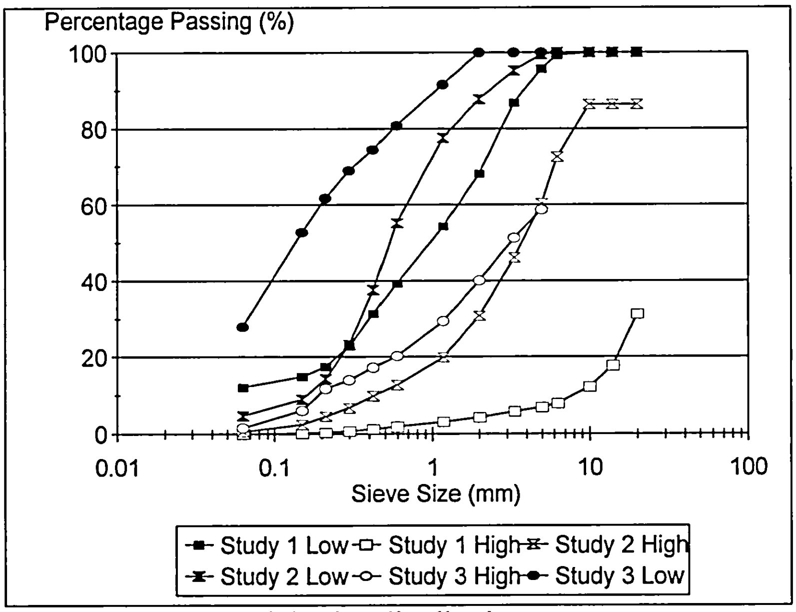


Figure 36 : Particle size distribution range summary (Inorganic fraction only)

Comparison of the near bed solids and deposited sediment characteristics, indicated that there was also some degree of similarity, as illustrated in Figures 37 and 38. This indicates that there may be transfer of solids between the near bed solids mode of transport and semi permanent sediment deposits, particularly at the higher and lower stages of the average DWF hydrograph. The same observation may also be made with the data collected by Lin et al. (1993a & b) in a trunk sewer where the near bed solids d_{50} was 2.0mm and the d_{50} range for the invert sediment was 0.3mm - >10mm (average 2.0mm). Laplace et al. (1992) and Bachoc et al. (1993) observed that (inorganic) particles up to 1.5mm would settle just after peak DWF velocities, it is unlikely that such particles would be transport in any other mode other than near bed solids transport. Indeed the French researchers (Lin et al., 1993a & b and Bertrand-Krajewski et al., 1995) postulate that if the material entering the trunk sewer transported as near bed solids can be arrested the sediment problem in Marseilles would be alleviated.

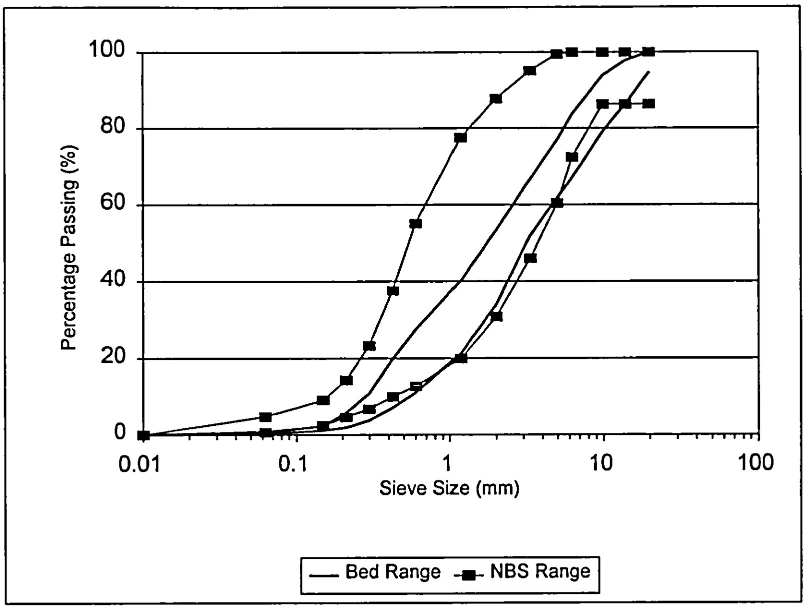


Figure 37 : Study Site 2 - Near bed solids (NBS) and invert sediment PSD range (Inorganic fraction only)

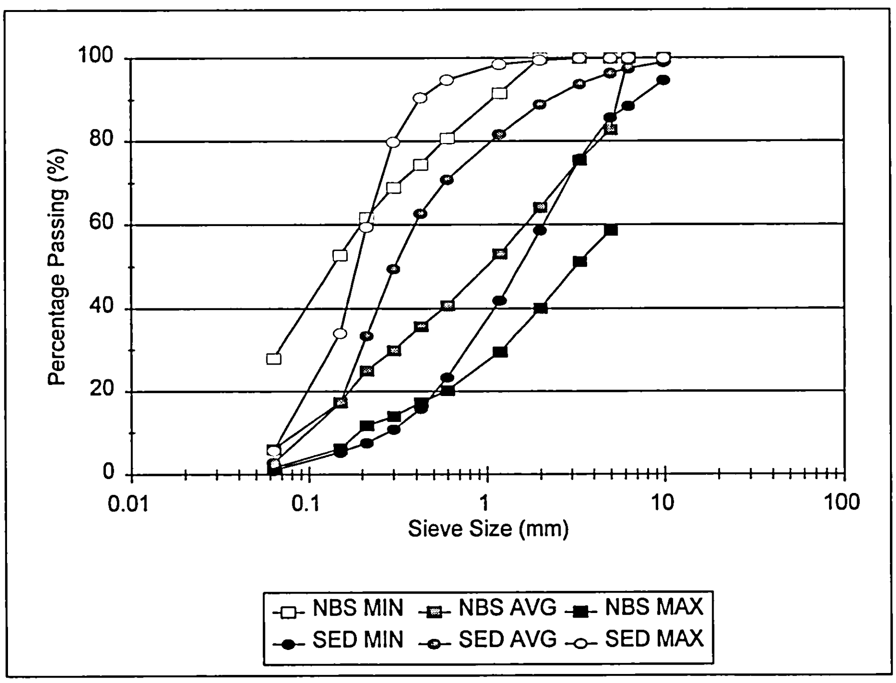


Figure 38 : Study Site 3 - Near bed solids (NBS) and invert sediment (SED) PSD range (Inorganic fraction only)

The particle size characteristics of the organic fraction of the near bed solids material obtained were also observed to vary considerably between Study Sites 2 and 3 in the interceptor sewer. The material collected at study site 2 was predominately large faecal (>10mm) solids and some food waste. At Study Site 3, where the data collection was more extensive, the material collected was almost entirely below 10mm in size and was more degraded. During low flow conditions the solids obtained were observed to be predominately composed of degraded paper waste, with only occasional faecal solids (see plates 13 & 14). Around lunch and evening time the proportion of food wastes (largely peas, sweet corn, shaped pasta and the like) in transport was seen to become significant, this reflects the perceived inputs to the system. Where samples were collected in the days immediately following rainfall events an increased number of earthworms were observed. At all other times the samples were observed to be composed principally of faecal solids, with some food and paper waste (see plate 15, 16, 17 & 18). As the sampling durations were always 48 minutes, or greater, any lag between the journey times of peak flows and associated near bed solids transport was not evident in the data collected.

6.3.1.1.2 Organic Content

The organic content was one of the main factors which highlighted the significant variations in the material collected at each of the study sites. The variation is illustrated in Table 36.

To test any sample for organic content a the sample is first dried at 105°C. Once dry the sample is then furnaced at 550°C. The percentage of the dry mass remaining is then designated the inorganic fraction, the dry mass lost in the furnace being the organic fraction. Where the mass of the inorganic fraction is low the results may be affected by the ashed residue of the organic material. This was found to be a problem when analysing the samples obtained from Study Site 3.

TABLE 36 : NEAR BED SOLIDS ORGANIC CONTENT VARIATION

	MIN (%)	AVG (%)	MAX (%)
Study Site 1 : DWF	0.5	7.1	61.5
: Storm	0.5	10.8	50.1
Study Site 2 : DWF	12.5	54.26	83.9
Study Site 3 : DWF	48.0	77.2	91.2

In a similar study undertaken by Bertrand-Krajewski et al. (1995) in a trunk sewer in France, average organic levels were 21.6% which compares well with the data from Studies 1 & 2, although no information is given regarding the hydraulic conditions at the French site. Whereas Ristenpart et al. (1995) report organic levels in excess of 90% ~10mm above the bed and Verbanck (1995) observed average organic levels

100mm above the bed of 90%, although both these observations are based on data collected using small bore samplers.

The data collected at Study Site 2 indicated that there was a definite variation in organic content throughout an average DWF day (between 05:00 - 15:00), this is illustrated in Figure 39. The data appear to indicate that as the velocity increases the inorganic fraction in the near bed solids increases. This may by due to the flow partially eroding some of the inorganic solids which have deposited during the night-time flow recession, and some of the organics moving at the bed shifting into suspension. Similar relationships were not observed at Sites 1 & 3, this may be due to several factors:

- Data collection at Study Site 2 was over a relatively short period, therefore there would be little variation in upstream conditions. Whilst the data collected at Sites 1 & 3 was collected over a longer period, and therefore seasonal changes may also be represented in the data collected in these studies.
- Small variations in the comparatively high organic contents observed at Study Site 3 may be difficult to detect.
- There was no upstream sediment bed at Study Site 1.
- The velocity conditions at Study Site 3 may not be sufficient to develop the same interaction with the bed, as observed at Study Site 2.

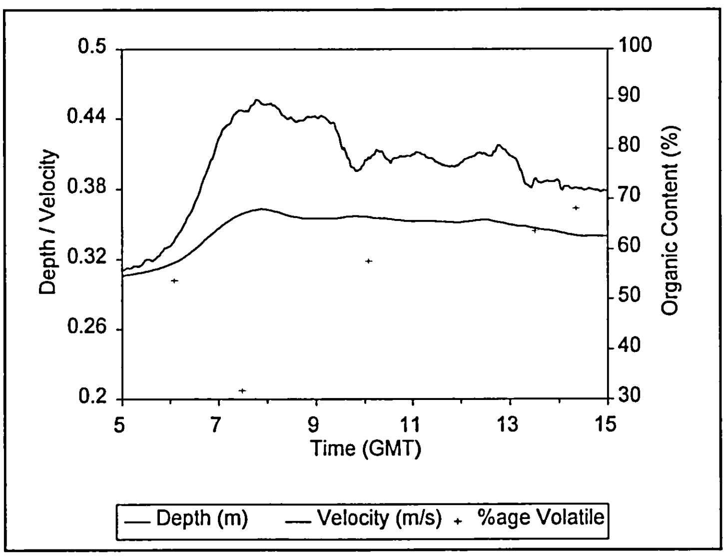


Figure 39 : Study Site 2 - Organic content variation

6.3.1.1.3 Bulk Density

Significant variations in the bulk density of the material in transport at the bed were observed between the data collection sites, as summarised in Table 37.

TABLE 37 : NEAR BED SOLIDS BULK DENSITY VARIATION

	MIN (kg/m^3)	AVG (kg/m^3)	MAX (kg/m^3)
Study Site 1 : DWF	1178.6	1517.9	1443.3
: Storm	1045.5	1583.9	1995.4
Study Site 2 : DWF	<1000[#]	1096.2	1233.4
Study Site 3 : DWF	<1000[#]	≅ 1000	1063.1

As with the particle size analysis, the near bed solids density variation between sites is hypothesised as being principally due to four factors which may be interrelated;

1. Ambient hydraulic conditions.

   At higher bed shear levels some of the organic particles, and smaller inorganics may move into suspension, thus influencing the average bulk density of the material in transport at the bed.

2. Upstream catchment characteristics.

   This is principally due to the material in transport at the bed being hypothesised as the main source of material which forms sewer sediment deposits (Ashley & Verbanck, 1996). Where an upstream deposit has been eroded this may cause some of the material in transport at the bed to settle and form a deposit. If no erosion has taken place for some time (long ADWP) any upstream sediment deposit may have reached its equilibrium level, and the transport capacity of the near bed solids mode of transport would be maintained.

3. Sediment supply rate.

   Solids inputs to the system will vary considerably throughout the DWF pattern.

4. Solids input characteristics.

   In section "6.3.1.1.1 Particle Size Distributions" it was described how the nature of the material in transport throughout a DWF period varied.

[#] Where samples had high organic contents, bulk densities of less than 1000kg/m^3 have been measured. This apparent anomaly may be due to errors in sample testing due to bio-degradation and human error, however it does reflect the low specific gravity of these samples.

It was observed that the sediments with low bulk density had high organic contents, with associated moisture contents. The highest density samples were the predominately inorganic samples obtained at Study Site 1.

Samples retrieved from Study Site 3 were observed, typically, to have a low bulk density, with little variation between samples with an average of ≅ 1000 kg/m^3 and a standard deviation of 86.13 kg/m^3. The lack of variation between the samples reflects the high organic content. This observation is supported by the observed variations in sample dry densities at Study Site 3, with an average of 80.7 and a standard deviation of 28.9 kg/m^3. The dry density levels observed at Study Site 3 were substantially lower than those obtained at other sites, as illustrated in Table 38.

TABLE 38 : NEAR BED SOLIDS DRY DENSITY VARIATION

	MIN (kg/m^3)	AVG (kg/m^3)	MAX (kg/m^3)
Study Site 1 : DWF	798.33	1182.8	1593.2
Study Site 2 : DWF	130.8	196.5	439.0
Study Site 3 : DWF	13.3	80.72	176.72

A weak correlation between dry density and the ambient velocity conditions was detected for the data collected at Study Site 3, as illustrated in Figure 40. A similar relationship could not be obtained for the data collected at Study Sites 1 and 2. This relationship is only indicative as other parameters must be involved (i.e. sediment supply characteristics).

The range of measured near bed solids bulk density observed at Study Site 1 is similar to that obtain by Lin et al. (1992a & b) who encountered material in the range 1921 - 2655kg/m^3. Lin et al. (1992a & b) used two sites for data collection; the first was at the head of the trunk sewer where flow velocities were relatively fast, the second was down stream with more tranquil flows and slacker invert gradients. Lin et al. (1993b) encountered a slight variation in particle density characteristics between sites. At the downstream site, however, Lin (1993) found that, although there was little difference in the material bulk density, the density of larger individual particles was less than that collected upstream. Lin (1993) found, for example, that at the upstream site the average density of a 10mm particle was 2655kg/m^3, whilst at the downstream site the average density was 1500 kg/m^3.

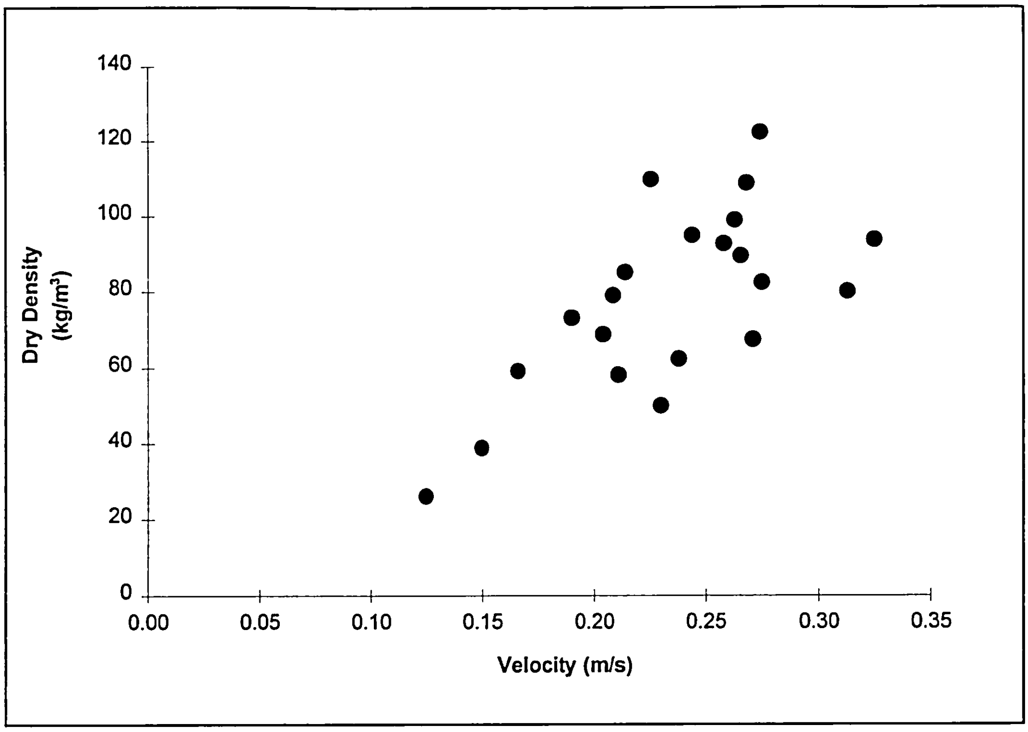


Figure 40 : Observed relationship between dry density
and average velocity conditions at Study Site 3

6.3.1.1.4 Settling Velocity

Due to equipment problems, only limited settling velocity tests were undertaken for the near bed solids samples obtained at each of the sites, with the emphasis being on the material collected at Study Site 3. It proved difficult to obtain settling velocity data for the material moving at the bed as an undisturbed sample of material is required. However, the results given in this section supply an indication of the range. The settling methodologies employed, and the results obtained over the duration of this study are discussed in more detail in Appendix C.

At study site 3 the entire sample was tested together (organic + inorganic) using a test methodology based on that proposed by the Scottish Development Department (S.D.D., 1980). The methodology gave median settling velocities in the range 2.1 - 10.1 mm/s, with 5% - 32% of the solids having a settling velocity in excess of 10.1mm/s. Samples obtained when velocity conditions were low were at the lower end of this range. Settling velocity tests carried out on the material moving at the bed obtained via sampling using small bore sampling hoses had a median settling velocity of 3.5 - 4.5mm/s, whilst sewage had a range of 0.75 - 3mm/s.

At Site 1, only settling velocities for the inorganic fraction of the sample was tested, and the median settling velocities were found to be 15-45mm/s. As the samples obtained from this site were principally inorganic these results give a good estimation of the actual settling velocity of the material.

Sample settling velocity results are given in Figure 41, The samples illustrated in the figure are obtained at 4 heights above the bed (5mm, 150mm, 300mm and 450mm) using small bore sampling hoses. The figure shows that the material sampled moving nearest the bed ('Tube 1') had the highest settling velocity.

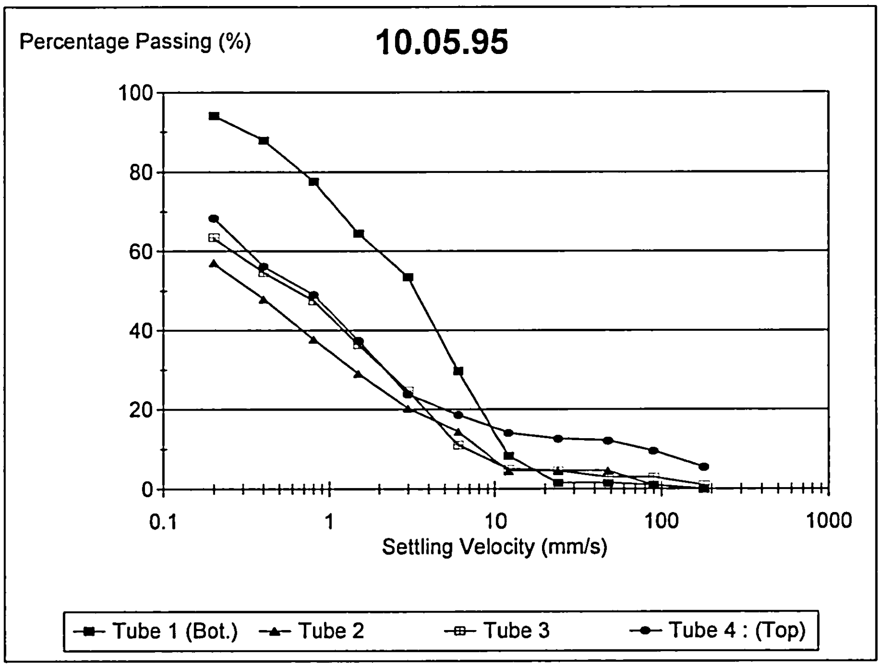


Figure 41 : Settling velocity data - Study Site 3

The settling velocities observed as part of the near bed solids monitoring were far lower than those measured by Lin et al. (1993a) who obtained median settling velocities in excess of 400mm/s at the upstream site, which may due to the data being collected in a trunk sewer and the non-selective nature of French gully pots.

The comparatively low settling velocity results obtained in Dundee reflect the low specific gravity of the material in transport, and illustrate how easily the material may be re-entrained to higher in the flow column during elevated flow conditions.

6.3.1.2 Pollutant Characteristics

An attempt was made to determine the pollutant potential of the near bed solids at each of the study sites. At Study Sites 1 and 2, only limited analysis of the samples was undertaken due to limited laboratory staff time. At Study Site 3, however, a more concerted effort was made in establishing the pollutant characteristics of the material. The tests carried out were for the following parameters;

- Ammonia
- Chemical Oxygen Demand (C.O.D.)
- Five day Biochemical Oxygen Demand (B.O.D.$_5$), which establishes approximately 60 - 70% of the ultimate B.O.D. (Metcalf and Eddy, 1991).

Table 39 illustrates the pollutant concentration of the solids obtained from each site. It is difficult to make direct comparisons between the data sets as the samples were often stored for protracted lengths of time (at -18°C) before testing was undertaken.

TABLE 39 : NEAR BED SOLIDS AVERAGE POLLUTANT CONCENTRATION

	COD (mg/l)	**BOD_5 (mg/l)**	**Ammonia# (mg/l)**
Study Site 1	87522	28594	248
Study Site 2	214000	82758	214
Study Site 3	124246	96119	181

TABLE 40 : NEAR BED SOLIDS POLLUTANT CONCENTRATION
STUDY SITE 3

	COD (mg/l)	**BOD_5 (mg/l)**	**Ammonia (mg/l)**
Minimum	50600	28280	41.3
Average	123083	98111	171.1
Maximum	288000	226090	519.7
Stand. Dev.	47441	44175	92.7

Where Study Site 3 is concerned the average values illustrated above may be misleading as the results here reflect data collected over a substantial part of the DWF pattern, and seasonal changes. The results for Study Site 3 are summarised in more detail in Table 40.

The table illustrates the considerable variation in the pollutant potential moving at the bed, even when obtained from the same site. No discernible relationship was observed relating any of the pollutant characteristics to the time in the DWF pattern at which the sample was retrieved, this may be due to the duration over which the field site was used (i.e. any long term or seasonal changes in the catchment would

It is possible to make direct comparisons between the ammonia levels at the sites as each data collection was undertaken in the spring summer months, thus avoiding any potential influence winter salting may have (Milne, 1996).

have to be accounted for). Attempts were made to relate the pollutant characteristics to other parameters, but no reliable relationship was observed, other than that for ammonia. A tentative relationship was obtained via multiple regression of measured parameters, which is illustrated in equation 157;

$$NH_4 = 3918.3 + 591.3V + 10.962\left(\frac{V}{V_{max}}\right) - 50.463\left(\frac{y_o}{y_{max}}\right)\ (\mathrm{mg/l}) \qquad ....157$$

Where V is the mean flow velocity and V/V_{max} represents inputs to the system, where *V* is the velocity at the time of day the samples were obtained, as the proportion (%) of the average DWF maximum depth. The same average DWF hydrograph was used for all the data sets. The definition of y_o/y_{max} is similar to that for V/V_{max}, but y_o is the depth at the time of day the samples were obtained. The relationship was obtained via multiple regressions, and has an r^2 value of 81.4%, the application of the resultant equation is illustrated in Table 41, where data set 2 was used for verification, data sets 3 - 17 were used to develop it. The range of flow data on which the relationship is based is given in Table 42. That ammonia levels are related to inputs to the system is not unexpected during DWF as ammonia levels in sewage are almost wholly associated with human activity.

TABLE 41 : AMMONIA LEVEL PREDICTION

Data Set	2	3	4	5	6	7	9	10
Measured Ammonia (mg/l)	119	76	209	143	124	141	87	144
Calculated Ammonia (mg/l)	100.3	97.4	191.1	165.4	118.9	155.5	141.0	132.9
Accuracy (%)	84.1	127.8	91.3	116.0	96.0	110.4	162.8	92.0

Data Set	11	12	13	14	15	16	17
Measured Ammonia (mg/l)	180	218	246	265	205	339	214
Calculated Ammonia (mg/l)	207.2	209.8	200.1	207.7	191.1	364.4	174.8
Accuracy (%)	115.3	96.2	81.4	78.4	93.3	107.4	81.8

TABLE 42 : RANGE OF PARAMETERS USED FOR AMMONIA PREDICTION

	MIN	MAX	AVG	S.D.
V (m/s)	0.12	0.32	0.23	0.05
V/V_{max} (%)	44.0	99.0	83.1	18.1
y_o/y_{max} (%)	85.0	100.0	95.2	4.73

The ratios V/V_{max} and y_o/y_{max} were used to represent solids input to the system as is has been established (Crabtree et al, 1993) that solids inputs to the system are directly related to flow liquid inputs, and hence flow conditions.

Because this relationship is site specific it does perform reasonably well, with 80% of the results being within the range ±20% of the measured value. The relationship also illustrates parameters which may play a role in the prediction of ammonia levels at other sites.

The pollutant data confirms the high pollutant potential of the material moving at the bed in the Dundee combined sewerage system, and further afield, and that important consideration should be given to the movement of this material in sewers. Table 43 compares the pollutant potential of near bed solids to that of sewage, which highlights the relative pollutant strength. However, although the near bed solids have considerable pollutant potential, the material transported in suspension represents the majority of the dry mass of solids and other pollutants in transport per unit volume.

TABLE 43 : SEWAGE, NEAR BED SOLIDS & DEPOSITED SEDIMENT AVERAGE POLLUTANT POTENTIAL - STUDY SITE 3

	SEWAGE			NEAR BED SOLIDS			DEPOSITED SEDIMENT		
	HIGH	LOW	AVG	HIGH	LOW	AVG	HIGH	LOW	AVG
BOD (mg/l)	632.2	34	331	151200	31111	96119	17500	1895	7125
COD (mg/l)	834	138	503	207400	84800	124246	16000	508	7166
AmmN (mg/l)	28.7	7.4	18.0	339.3	76.2	181	1120	6	163

6.3.1.3 Transport Rates

This section deals with the rate of transport of material at the bed at each of the study sites, the results can be separated into two parts:

1. Sediment Transport Rates
2. Pollutant Flux

6.3.1.3.1 Sediment Transport Rates

The transport rate of sediment near the bed at each site is expressed in terms of C_v, the volumetric sediment concentration, as defined in equation 158:

$$C_v = \frac{\textit{Mass of Solids Transported}}{\textit{Mass of Flow} + \textit{Mass of Solids Transported}} \quad \text{....158}$$

Expressing sediment transport rates in terms of C_v does not represent the volumes of material in transport (i.e. 1kg of highly organic sample will represent a larger wet volume than 1kg of inorganic sample). Due to the low sediment concentrations observed in this study, it is possible to convert C_v (ppm) to mg/l, without incurring significant errors, due to the low material densities measured (i.e. $\rho_b \rightarrow \rho_w$).

Table 44 details the transport rates observed during DWF at Study Site 1. As the data illustrates, a considerable proportion of the total solids transported were transported at the bed ($\check{S}$, as defined in equation 159). The very low transport rates for the data collected over a duration of 1 hour (21.07.92) and 24 hours (27.07.92 & 29.07.92) indicates that the sediment trap may have filled before the end of the test, and this reflects the prototype nature of the work undertaken at Study Site 1 rather than, necessarily, the actual transport concentrations.

TABLE 44 : SUSPENDED AND NEAR BED SEDIMENT TRANSPORT RATES - STUDY SITE 1

	06.07.92	15.07.92	21.07.92	27.07.92	29.07.92
NBS (g/s)	35.67	7.33	1.67	2.04×10^{-3}	2.84×10^{-3}
NBS Density (kg/m^3)	1475	1513	1734	1521	1405
NBS C_V (ppm)	874.66	157.89	55.56	0.06	0.09
TSS (g/s)	9.97	8.13	6.34	4.73	-
Š (%)	78.2	47.4	20.8	0.04	-

$$\check{S} = \frac{\text{Mass of Solids Moving at the Bed}}{\text{Mass of Solids Moving at the Bed \& in Suspension}} \times 100\% \qquad \text{....159}$$

TABLE 45 : SEDIMENT TRANSPORT RATES - STUDY SITE 2

	1	2	3	4	5	AVG
NBS (g/s)	1.16	0.68	1.43	0.80	1.42	1.10
NBS Density (kg/m^3)	1098	1135	1158	1032	1038	1092
NBS C_V (ppm)	13.03	10.35	16.04	9.78	15.64	12.97
TSS (g/s)	10.35	11.09	17.39	12.38	22.54	14.99
Š (%)	10.1	5.8	7.6	6.1	5.9	7.1

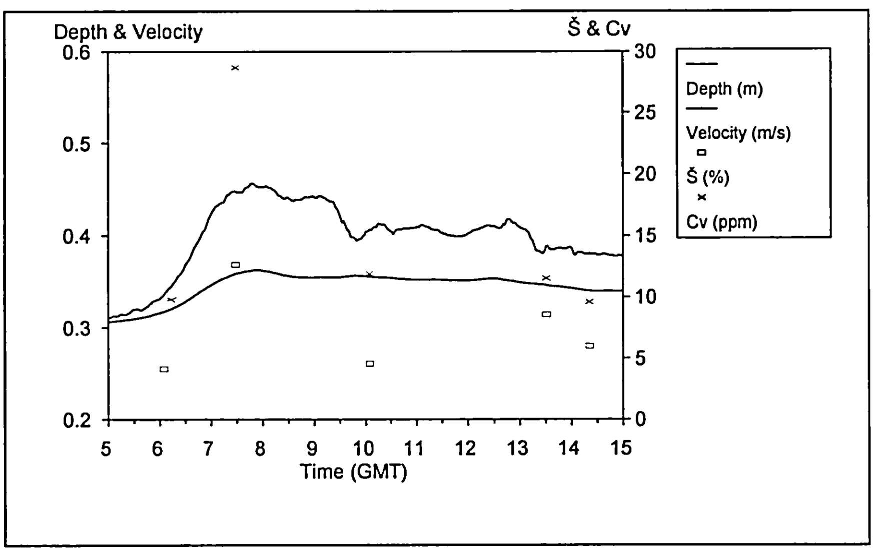


Figure 42 : Variation of C_V and Š with flow conditions and Study Site 2

Table 45 summarises the transport rates measured at Study Site 2. The data illustrate that, generally, the sediment transport rates, are considerably less than those observed at Study Site 1. This is possibly due to the higher ambient velocity conditions observed at Site 1. Additionally, the data indicate that the proportion of the total solids in transport moving at the bed is considerably less at this site, 5.8% to 10.1%. This confirms the work of Coghlan (1995) who estimated that up to 12% of the total mass in transport moved at the bed. The rate of near bed solids transport and Š are seen to vary with average DWF conditions, as illustrated in Figure 42. The variation in solids transport rate illustrated in the figure will principally be due to changes in inputs to the system and the ambient hydraulic conditions.

TABLE 46 : SEDIMENT TRANSPORT RATES - STUDY SITE 3

Data Set	**1**	**2**	**3**	**4**	**5**	**6**	**7**
C_V (ppm)	6.28	4.19	3.35	6.12	7.15	7.80	4.93
Sediment Transport Rates							
Total (mg/s)	309.0	313.3	266.1	395.0	459.0	456.4	302.5
Inorganic (mg/s)	137.9	81.9	46.3	99.5	80.3	71.9	55.9
Organic (mg/s)	171.1	231.4	219.8	295.5	378.8	384.4	246.5
Š (%)	-	2.19	1.35	2.46	2.64	3.20	1.68

Data Set	**8**	**9**	**10**	**11**	**12**	**13**	**14**
C_V (ppm)	4.40	4.12	1.97	1.63	3.85	3.00	3.50
Sediment Transport Rates							
Total (mg/s)	280.8	266.2	127.4	43.3	140.5	161.2	200.8
Inorganic (mg/s)	77.1	58.7	27.9	11.3	19.3	58.8	54.9
Organic (mg/s)	203.6	207.4	99.5	32.0	121.3	102.4	145.9
Š (%)	-	1.50	0.47	3.77	8.29	0.89	1.34

Data Set	**15**	**16**	**17**	**18**	**19**	**20**	**21**
C_V (ppm)	1.75	7.48	8.95	1.07	1.33	6.50	2.40
Sediment Transport Rates							
Total (mg/s)	84.7	489.2	467.4	50.8	61.0	109.0	30.5
Inorganic (mg/s)	18.3	71.7	105.6	7.9	15.8	16.1	2.7
Organic (mg/s)	66.5	417.5	361.8	42.9	45.2	93.0	27.8
Š (%)	4.58	3.67	-	0.60	0.72	3.78	2.49

Data Set	**MIN**	**AVG**	**MAX**	**STD**
C_V (ppm)	1.07	4.37	8.95	2.3
Sediment Transport Rates				
Total (mg/s)	30.45	238.7	489.2	149.9
Inorganic (mg/s)	2.69	53.33	137.9	36.0
Organic (mg/s)	27.80	185.4	417.5	122.1
Š (%)	0.47	2.54	8.29	1.84

At Study Site 3, where the largest range of data were collected, in terms of flow conditions and time of day, significant variations in sediment transport rates were observed, as illustrated in Table 46. Transport rates were lower than observed at other sites, with C_V in the range 1.07 - 8.95ppm (30.45 - 489.2 mg/s) with an average of 4.37ppm (238.7 mg/s). The proportion of solids moving at the bed was also observed to be less than that observed at other sites, with a range of 0.47 - 8.29%, and an average of 2.54%. The lower near bed transport rates may be due to temporal changes in the system, or the degradation of larger solids moving between the sites, the residue of which then move into suspension. The results may also be due to the lower relative density of the material in transport at the bed at Study Site 3, when compared to that for Study Sites 1 and 2.

The near bed sediment transport rates observed in Dundee are similar to those encountered in France by Lin et al. (1993b) using a similar sampling methodology. The estimated 'bed-load' transport rates reported by the French researchers are detailed in Table 47.

TABLE 47 : ESTIMATED FRENCH "BED-LOAD" TRANSPORT RATES
(adapted from Lin et al., 1993b)

	Sediment Transport Concentrations Cv			
Site	**MIN. (g/s)**	**AVG. (g/s)**	**MAX. (g/s)**	**AVG. Cv**
'Upstream'	0.55	1.9	4.29	14.6 ppm
'Downstream'	-	0.64	-	2.7 ppm

6.3.1.3.2 Pollutant Transport Rates

It is important to understand the pollutant potential of the material moving near the bed as, due to its relatively low specific gravity (as observed at Study Sites 2 & 3), it is probable that is a primary source of the pollutants associated with first foul flush phenomena (see section 2.6 "First Flush"). To assess this, this section will concentrate on the data collected at Study Site 3, as the data collected at this site are the most comprehensive.

Table 48 compares the rate of transport of the COD potential of the near bed solids with that in transport higher in the flow column ($\check{S}_C$ is defined in equation 160). It can be seen from the table that although the near bed solids transport represents a modest proportion of the total solids in transport in this sewer (up to 8.29%, see section 6.3.1.3.1 "Sediment Transport Rates"), the mode of transport conveys a considerable proportion of the COD potential of the wastewater (up to 43.43%). A similar observation can be made when considering the BOD_5 results, illustrated in Table 49 ($\check{S}_B$ is defined in equation 161), which indicate that the near bed solids mode of transport at this site conveys up to 54% BOD_5 for the flow. These results highlight the high organic content of the near bed solids in transport at this site, and demonstrates the need for more understanding of the factors which affect near bed solids transport in combined sewers in general.

$$\check{S}_C = \frac{\text{COD in NBS}}{\text{COD in NBS \& in Suspension}} \times 100\% \qquad \text{....160}$$

$$\check{S}_C = \frac{\text{BOD}_5 \text{ in NBS}}{\text{BOD}_5 \text{ in NBS \& in Suspension}} \times 100\% \qquad \text{....161}$$

The presence of a high COD level at the invert in combined sewers was also observed by Whorl and Brombach (1991), whilst obtaining samples via small diameter sampling tubes. A maximum COD of 2520 mg/l was measured at the bed, compared with an average of 568 mg/l.

TABLE 48 : NEAR BED SOLIDS COD TRANSPORT RATES
STUDY SITE 3

DATA SET	1	2	3	4	5	6	7
NBS COD (kg)	-	8.3	12.4	11.9	12.2	11.6	12.0
TSS COD (kg)	-	160.9	168.7	126.0	122.7	118.9	120.1
$\check{S}_C$ (%)	-	4.89	6.83	8.66	9.03	8.92	9.11

DATA SET	8	9	10	11	12	13	14
NBS COD (kg)	7.7	-	6.7	2.2	5.5	5.0	5.7
TSS COD (kg)	-	128.7	155.1	44.2	26.9	115.2	105.6
$\check{S}_C$ (%)	-	-	4.16	4.80	17.07	4.19	5.09

DATA SET	15	16	17	MIN	AVG	MAX	STD
NBS COD (kg)	15.9	25.4	21.6	2.2	11.2	25.4	6.1
TSS COD (kg)	20.7	104.9	-	20.7	101.4	168.7	44.9
$\check{S}_C$ (%)	43.43	19.51	-	4.16	10.45	43.43	10.37

TABLE 49 : NEAR BED SOLIDS BOD_5 TRANSPORT RATES
STUDY SITE 3

DATA SET	1	2	3	4	5	6	7
NBS BOD (kg)	-	5.5	-	-	10.4	9.6	7.1
TSS BOD (kg)	-	103.7	106.4	78.1	59.4	83.0	102.2
$\check{S}_B$ (%)	-	5.03	-	-	14.94	10.37	6.49

DATA SET	8	9	10	11	12	13	14
NBS BOD (kg)	5.0	-	5.4	0.8	6.9	7.6	8.5
TSS BOD (kg)	-	109.3	117.5	12.9	5.8	68.8	66.7
$\check{S}_B$ (%)	-	-	4.41	5.96	54.43	9.92	11.27

DATA SET	15	16	17	MIN	AVG	MAX	STD
NBS BOD (kg)	6.4	16.3	13.3	0.8	7.9	16.3	3.8
TSS BOD (kg)	5.3	73.1	-	5.3	49.4	117.5	37.1
$\check{S}_B$ (%)	54.37	18.26	-	4.41	14.94	54.43	17.73

A Similar analysis was undertaken in investigating the ammonia in transport at the bed in comparison with material transport in suspended mode. However, it was found that the majority of the ammonia was transported higher in the flow column, as illustrated in Table 50 ($\check{S}_A$ is defined in equation 162). The data indicated that the transport of material at the bed accounts for only 0.28 - 1.33% of the total ammonia transported. This is due to ammonia mainly being transported in the dissolved phase in waste waters, and although the material in transport at the bed has been shown to carry a higher concentration of ammonia, the amount is not disproportionate, as observed with COD and BOD_5.

$$\check{S}_C = \frac{\text{Ammonia in NBS}}{\text{Ammonia in NBS \& in Suspension}} \times 100\% \qquad \text{....162}$$

TABLE 50 : NEAR BED SOLIDS AMMONIA TRANSPORT RATES STUDY SITE 3

DATA SET	**1**	**2**	**3**	**4**	**5**	**6**	**7**
NBS Ammonia (g)	-	9.6	7.2	22.8	14.1	11.8	13.1
TSS Ammonia (kg)	-	2.4	-	3.8	4.1	1.2	2.7
$\check{S}_A$ (%)	-	0.40	-	0.60	0.34	0.94	0.48
DATA SET	**8**	**9**	**10**	**11**	**12**	**13**	**14**
NBS Ammonia (g)	7.8	-	9.7	4.7	12.9	12.3	16.5
TSS Ammonia (kg)	-	2.2	2.6	1.7	1.0	4.3	5.1
$\check{S}_A$ (%)	-	-	0.37	0.28	1.31	0.29	0.32
DATA SET	**15**	**16**	**17**	**MIN**	**AVG**	**MAX**	**STD**
NBS Ammonia (g)	17.5	41.6	23.5	4.7	15.0	41.6	8.8
TSS Ammonia (kg)	1.3	4.8	-	1.0	2.9	5.1	1.4
$\check{S}_A$ (%)	1.33	0.86	-	0.28	0.63	1.33	0.37

6.3.2 Suspended Solids Transport

As illustrated in section 6.3.1.3 “Transport Rates” the majority of solids, and associated pollutants, are generally transported in the suspended mode of transport in sewers.

In most cases, when near bed solids samples were retrieved, suspended solids samples were also retrieved. As the majority of the sampling durations were periods of 48 minutes, or less, little temporal variation in suspended solids concentration is evident during these periods. A summary of the suspended solids profiles for each of the data sets is given in Appendix D. The data in the Appendix also gives details of COD, BOD_5 and ammonia levels for each of the sewage samples where this analysis was undertaken. A summary of the average solids concentrations and pollutant potential measured at each of the study sites is given in Table 51. Average values are also given for between 5am and 3pm as this when all the data collection took place at Study Sites 1 and 2.

TABLE 51 : SEWAGE POLLUTANT SUMMARY FOR STUDY SITES 1, 2 AND 3

Site	TSS (mg/l)	VSS# (mg/l)	Volatile (%)	COD (mg/l)	BOD (mg/l)	Ammonia (mg/l)
Site 1	147.9	118.4	80.1	NOT MEASURED		
Site 2	175.8	151.6	86.2	487	254	29.2
Site 3 - 24hrs	177	149	84.2	503	331	18.0
5am - 3pm	216.8	190.8	88.0	600	399	15.0

TABLE 52 : POLLUTANT CONCENTRATION WITH DEPTH STUDY SITE 2

Date	**29.04.93**	**13.05.93**	**19.05.93**	**25.05.93**	**27.05.93**
Start Time	13:06	05:41	06:53	13:51	09:40
Duration (m)	48	48	72	48	48
Cumulative SS (kg)	28.47	32.16	51.11	35.55	65.07
SS Transport (kg/h)	35.6	40.2	42.6	44.4	81.33
Avg. TSS - Top (mg/l)	109.6	109.8	193.2	147.4	200.9
Avg. TSS - Bot (mg/l)	123.1	226.4	197.5	154.5	295.5
Avg. TSS (mg/l)	116.3	168.1	195.4	150.95	248.2
Top-TSS : Bot-TSS	1 : 1.123	1 : 2.061	1 : 1.022	1 : 1.048	1 : 1.470
Avg. VSS - Top (mg/l)	104.1	97.3	158.7	130.5	179.7
Avg. VSS - Bot (mg/l)	115.7	171.0	161.0	136.9	261.1
Avg. VSS (mg/l)	109.9	134.2	159.8	133.7	220.4
Top-VSS : Bot-VSS	1 : 1.111	1 : 1.760	1 : 1.014	1 : 105	1 : 1.453
Avg Vol SS - Top (%)	95.0	88.6	82.1	88.6	89.45
Avg Vol SS - Bot (%)	99.4	75.66	81.5	88.6	88.34
Avg. COD - Top (mg/l)	471.6	264.9	523.9	535.2	578.3
Avg. COD - Bot (mg/l)	460.9	445.3	459.4	540.8	596.1
Avg. COD (mg/l)	466.2	355.1	491.6	537.8	587.2
Avg. BOD - Top (mg/l)	123.3	-	-	225.9	316.2
Avg. BOD - Bot (mg/l)	152.5	-	-	261.3	446.5
Avg. BOD (mg/l)	137.4	-	-	243.6	381.4
Avg. NH_4 - Top (mg/l)	17.9	-	24.1	40.3	42.6
Avg. NH_4 - Bot (mg/l)	19.55	-	31.1	31.41	26.9
Avg. NH_4 (mg/l)	18.7	-	27.6	35.9	34.7

For each of the sample sets obtained as part of the data collection at Study Site 2 sewage was collected from two depths in the flow. As the sampling tubes were semi-rigid it meant that as the flow depth varied so did the relative position of the tube in the flow. The bottom tube was positioned approximately 150mm above the invert of the flume, and the top approximately 100mm higher.

Volatile suspended solids concentrations are approximate only. This is principally due to the nature of the test, in that filter papers are exposed to high temperatures (480°C) to remove the organic fraction, which causes some reduction in the mass of the 'paper' itself. This error is normally insignificant, other than where organic contents are very high (→100%) or where the concentration of total solids is very low. Where this is a problem VSS levels of 100% have been assumed.

The data relating to the variation of suspended solids, and associated pollutants, are detailed in Table 52. As illustrated in the table, it was found that total suspended solids and BOD_5 concentrations were higher where sampled near the bed. The suspended solids results confirm the findings of several other researchers in the field (e.g. Verbanck, 1995 & Ristenpart et al., 1995, etc.). For COD and ammonia, however, the data reveal no real trends, suggesting these pollutants may not be associated with the suspended phase. These results are somewhat ambiguous as it is recognised that BOD_5 is normally associated with the solids phase in waste waters, and COD is normally identified with dissolved pollutants (Metcalf &Eddy, 1991). These results must then be treated with some degree of scepticism, especially when the uncertainties associated with the positions of the two sampling hoses in the flow are also taken into account.

At Study Site 3 a more detailed attempt was made to investigate suspended solids variation with depth. This was undertaken by obtaining samples, via small diameter tubes at pre-determined positions in the flow column, namely 5mm, 150mm, 300mm and 450mm above the invert. There were a number of reasons why samples were collected in this manner:

- To attempt to obtain a suspended solids profile in the flow column.
- To allow a better comparison of the material moving at the bed in Dundee with the 'dense undercurrent' observed by Verbanck (1995).
- To compare the results of sampling the near bed solids via the invert traps and small diameter sampling hoses.

The average concentration variation of TSS, VSS, COD, BOD_5, and ammonia is given in Figure 43 and detailed in Table 53. Full details of the suspended solids concentration with depth of each of the 5 sample sets obtained are given in Appendix E.

From the data, a definite pollutant concentration gradient can be observed for each of the pollutants measured, other than ammonia, can be observed. As with the data collected at Study Site 2 this may indicate that ammonia is principally associated with the dissolved load, whilst BOD_5 and COD are associated with the larger solids in transport.

The suspended solids profile was not as pronounced as that observed by Ristenpart et al. (1995) who obtained samples of near bed solids moving 10mm above a deposited sediment bed using small bore samplers. It is not clear, however, to what extent the sampler obtained samples of the near bed solids and what proportion came from the deposited bed.

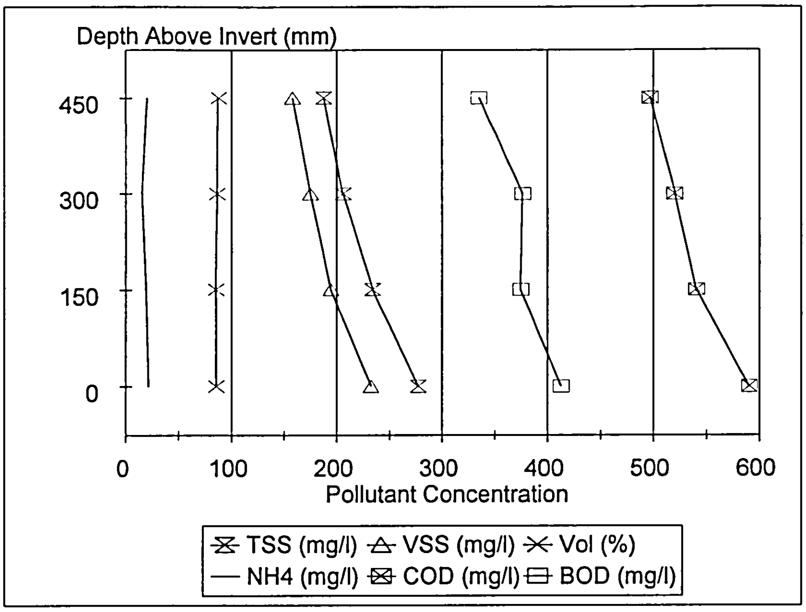


Figure 43 : Average pollutant concentration variation with depth

TABLE 53 : AVERAGE POLLUTANT CONCENTRATION WITH DEPTH STUDY SITE 3

Height Above Invert (mm)	TSS (mg/l)	VSS (mg/l)	Vol (%)	NH4 (mg/l)	COD (mg/l)	BOD (mg/l)
~0	277.7	232.8	85.6	21.5	590.6	413.2
150	234.3	194.4	85.5	19.3	540.8	374.7
300	206.3	174.9	86.6	19.2	520.3	376.5
450	187.9	157.9	88.0	20.5	497.1	335.5

An attempt was made to relate the suspended solids profile to other measured parameters, this was unsuccessful. This may have been due to:

- The velocity profile - this was not logarithmic as the pipe was often running nearly full.
- Settling velocity results - equipment availability problems meant settling velocity data were not detailed enough to involve this parameter in the analysis.
- The presence of the sampling hoses in the flow would have affected the flow pattern.
- The unsteady nature of the flow at Study Site 3.

It was found that using small diameter tubes to sample the material moving at the bed was ineffective. This was principally due to the hoses being continually blocked by the larger solids. Partial blocking of the hoses at the bed also resulted in samples with lower than expected suspended solids levels, as the materials causing the blockage effectively operated as a filter.

Although these data confirm that a pollutant concentration profile does exist in sewers, it must be remembered that the vast majority of the sediment transported in suspension is carried higher in the flow column, as illustrated in Figure 44. Hence, the position of the sampling point in the flow column is an important factor when collecting sewer flow quality data. The zones illustrated in the figure are illustrated in Table 54.

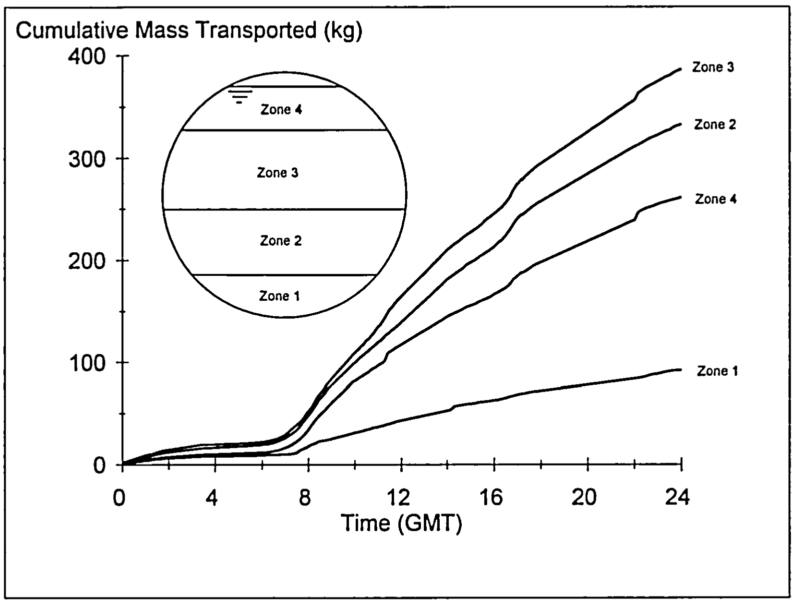


Figure 44 : Cumulative transported mass for each of the zones in the flow column

As described above, it is believed that the small diameter hoses did not give accurate representation of the material in transport at the bed, however, if it is assumed they do, then it is possible to obtain an estimation of the size of zone in which the near bed solids are transported. In doing this the following assumptions must be made:

- There is a clear definition between suspended and near bed solids modes of transport, and there is no transitional zone (Verbanck, 1995)
- The sampling of the near bed solids via the small diameter hoses gives an accurate estimation of solids concentration at the bed (Verbanck, 1995).
- The invert traps used in Study 3 give an accurate estimation of the near bed solids transport rate.

Based on these assumptions it was estimated that the near bed solids were transported in the zone up to 37mm above the invert (7.3% of the flow depth, or 3.0 % of the flow area). This results compares well with the assertions of Verbanck

(1995), who estimated that his 'dense undercurrent' moves in the bottom 10% of the flow column, although little direct evidence is available to support this finding.

TABLE 54 : PROPOSED SEGREGATION OF FLOW COLUMN USED TO ESTIMATE CUMULATIVE MASS TRANSPORTED

Zone	Sampling Hose Position (mm above invert)	Zone Range (mm above invert)	Zone Area (mm^2)	Zone Flow (% of total)
1	~0	0 - 50	10851	6.30
2	150	50 - 225	81679	30.4
3	300	225 - 375	82762	37.8
4	450	375 - Depth	52959 (AVG)	25.5

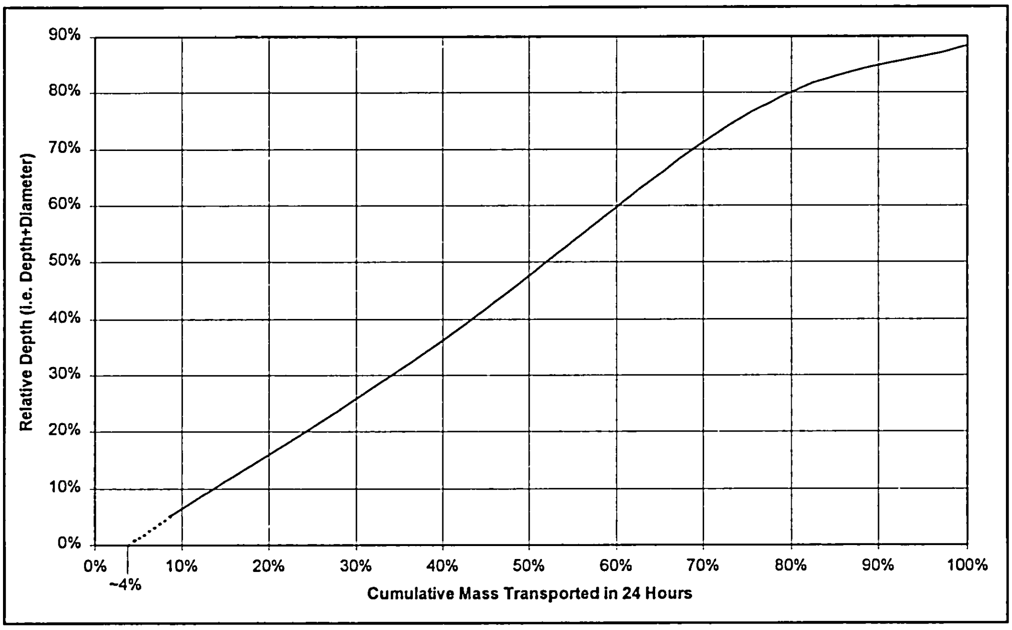


Figure 45 : Total solids transported variation with depth for Study Site 2

For the data collected at Study Site 3, Figure 45 illustrates the cumulative mass of dry solids transported over 24 hours for each part of the flow column. Although this is reliant on data collected at only four points in the flow column using small bore samplers, it shows that approximately 4% (which represents 31kg dry or ~450Kg wet) of the solids are unaccounted for. As it is known that the small bore samplers do not represent all of the material in transport near bed it can be postulated that 4% of solids which are not accounted for are those which are not sampled by the sampler.

6.3.3 Gross Solids Transport

To complement the work at Study Site 3, gross solids transport throughout the flow column was also monitored using similar methods to those used by other researchers (Milne et al, 1995). The gross solids were collected using an open weave "Copa" sack (6mm) secured over one end of a 100mm internal diameter pipe. The pipe was placed in the flow with the free end facing into the flow, any solids in the flow larger than 6mm were then trapped in the Copa sack (see plate 19).

The data collected indicated that there was no discernible zone in the flow column where gross (sanitary) solids are preferentially transported. It was also observed that most of the paper in the flow was broken down (<20mm) by the time it had reached the site used in Study 3. Gross solids transport rates were estimated at this site and were found to be in the range 0.81 - 2.49g/s (dry mass). Although this represents a sizeable amount of material in transport it was evident that much of the material sampled could also be considered as suspended load, as similar particles were frequently sampled using wastewater samplers.

6.4 Evidence of Foul Flush

Due to the inherent dangers of operating in a large combined interceptor sewer during storm conditions it was only possible to collect one storm data set at Site 3. This showed clear evidence of a flush of pollutants. The storm hydrograph and sedograph are illustrated in Figure 46, the rainfall depth in Figure 47, the flush characteristics in Figure 48, and sediment transport for a similar DWF time period is shown in Figures 49a and b. Table 55 illustrates the difference in the total material transported between storm and DWF conditions.

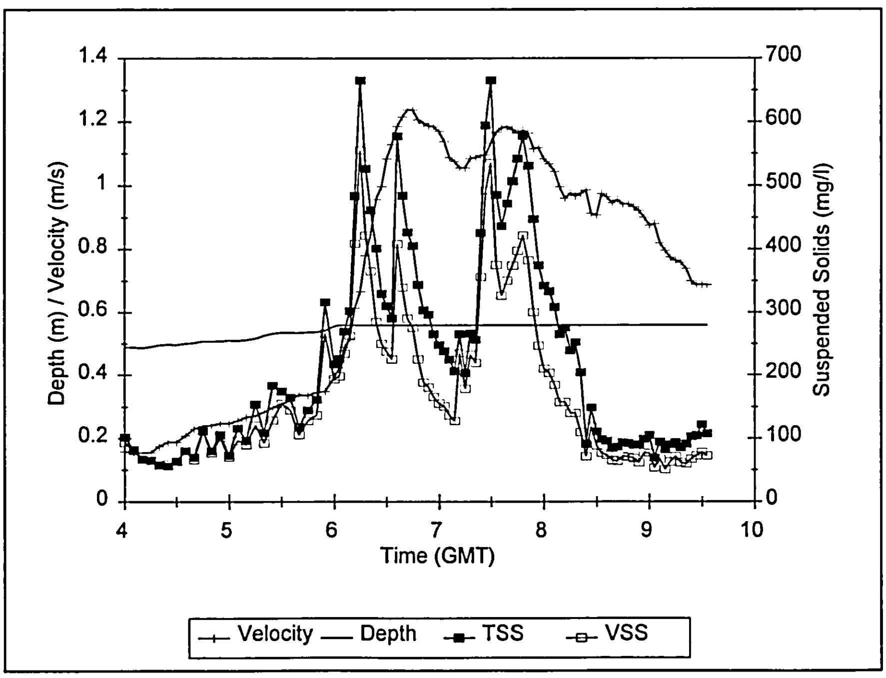


Figure 46 : Storm hydrograph and sedograph - 11.09.94

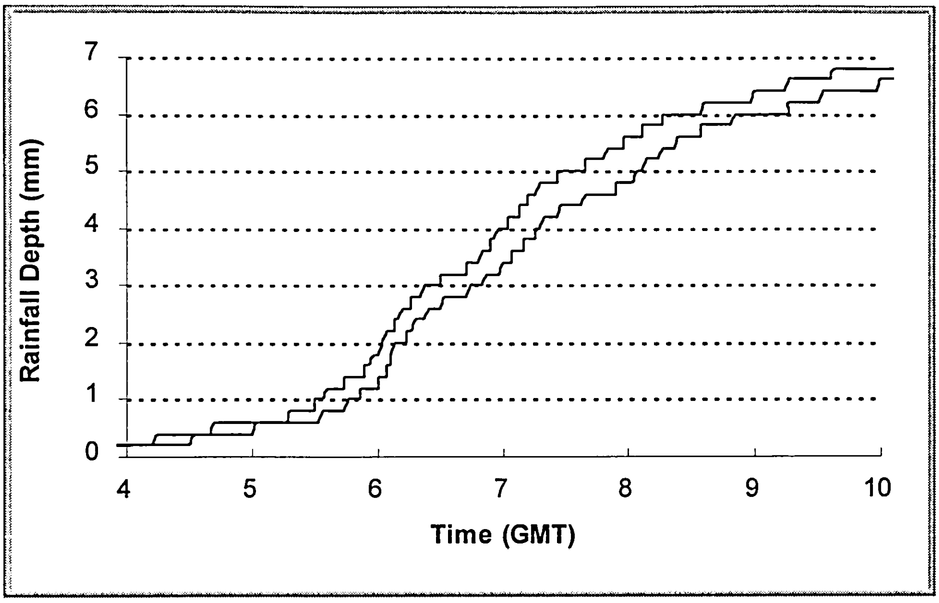


Figure 47 : Storm cumulative depth of rainfall - 11.09.94#

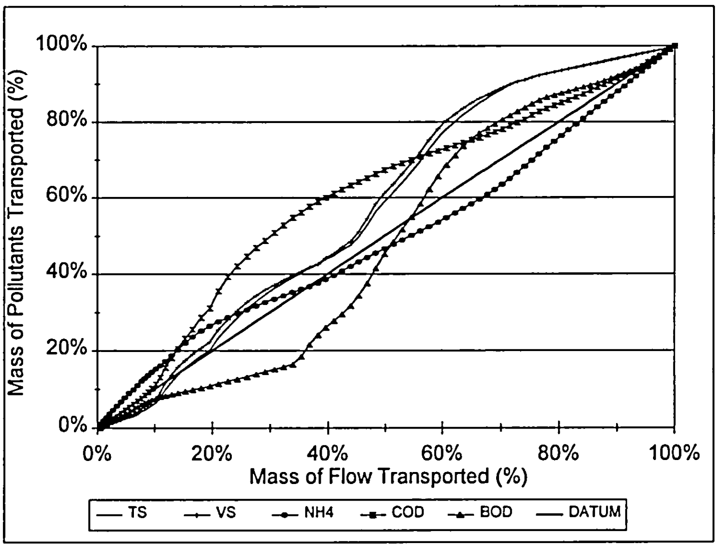


Figure 48 : Evidence of first flush (05:00 - 09:30) - 11.09.94

The catchment which contributes to Study Site 3 was monitored by 2 rain gauges, and the data from both of these is given in the figure.

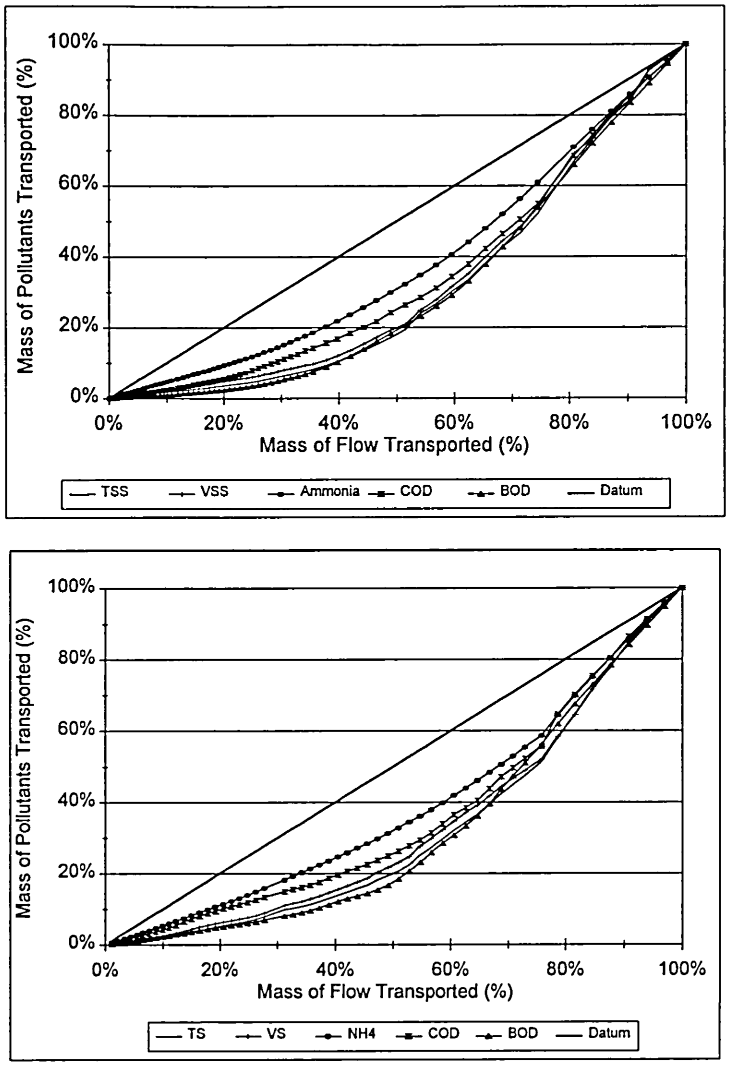


Figure 49a & b : DWF pollutant dilution (05:00 - 09:30)

TABLE 55 : DWF/STORM COMPARISON#

	Flow (m^3)	TSS (kg)	VSS (kg)	Ammonia (kg)	BOD (kg)	COD (kg)
DWF	554	93.8	83.05	8.75	109.55	246.4
Storm	3350	948.4	692.4	11.70	271.9	920.1
Difference (%)	+505%	+911%	+734%	+33%	+148%	+273%

From the figures, a definite flush of COD and suspended solids can be observed, although suspended solids appear to be affected more by the second peak in the flow (07:45). This may be due to the availability of solids from domestic and industrial inputs, before the morning peak the suspended sediment concentrations are observed to be relatively low. It is difficult to draw any firm conclusions as to the nature of the first foul flush phenomena in this sewer as there is only one data set and it relates to

The storm data illustrated in this table refer only to the flow passing through the test rig. Under most storm conditions the whole test site typically became flooded, this resulted in substantial amounts of flow passing over the test rig, along with the associated solids.

a point in the DWF pattern which normally experiences substantial changes in flow and solids levels.

The BOD exhibits a dilution within the initial stages of the storm and then, later, exhibits a flush which coincides with the second peak in TSS concentration. It is difficult to ascertain why this is the case as the data set relates to a point in the DWF pattern which normally experiences substantial changes in flow and solids levels.

In the same sewer, Wotherspoon (1994) observed, using a sonar bed depth monitor, a distinct increase in the apparent depth of the deposited sediment depth immediately prior to erosion during some storm events. Wotherspoon (1994) hypothesised that this may be due to the attenuation of the sonar 'beam' by material in transport just above the bed. This indicates that the near bed solids may be rapidly entrained to higher in the flow column at the onset of storm flows.

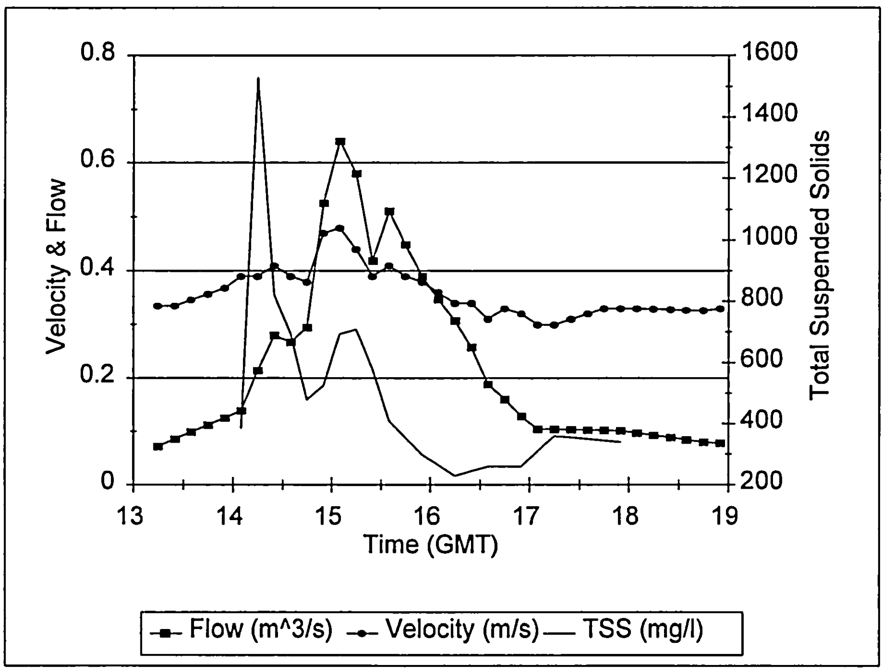


Figure 50 : Interceptor storm pollutograph - 27.01.89
(adapted from Ashley, 1993)

Additional first flush data relating to the occurrence of the first flushes in the Dundee Interceptor sewer are available from (Ashley, 1993 and Coghlan, 1995). However, due to the large time step at which these data were collected and the omission of the start of the storm from some data sets the significance of this data is limited, Figures 50 and 51 illustrate data for a storm which occurred on 27th January 1989, with the latter figure showing a flush of suspended solids level. Based on these data it can be seen that, although foul flushes do not occur in all sewer systems, they do occur in the Dundee Interceptor sewer.

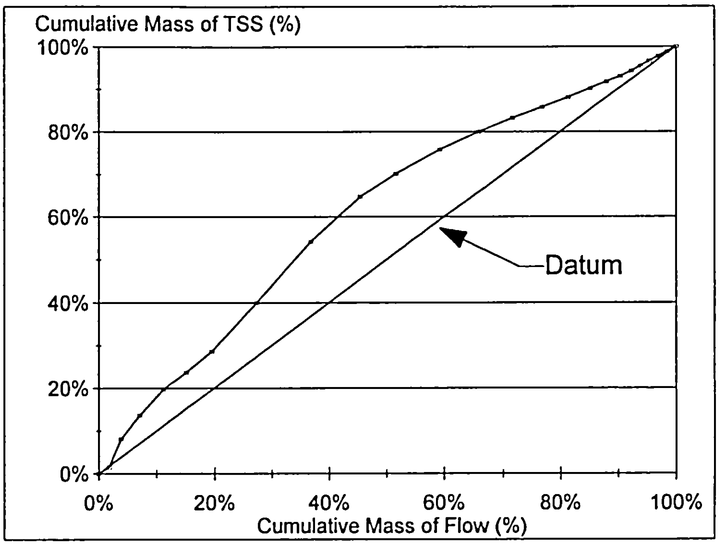


Figure 51 : Interceptor flush diagram - 27.01.89

6.5 Discussion

The data presented in the preceding sections of this chapter have confirmed the high heterogeneity of the material in transport in the observed combined interceptor sewer. The high pollutant potential of the material in transport, together with the low specific gravity means that it may be easily eroded into suspended sediment transport, and may add to the potential impact of first foul flush phenomena.

Traditionally the source of material for the solids in the first foul flush have been believed to be from sewer sediments, surface sediments, gully sediments, pipe slimes etc. However, if a sewer length is considered which has no deposited sediment bed (as outlined in section 2.6 'First Flush'), and no lateral inputs, a storm wave will move along it as idealised in Figure 52.

The figure represents the flow passing a single point in a systems over a given time step (i.e. the x-axis is time).

It is possible to consider the storm wave segregated into three discrete sections each with a different ambient velocity;

u_w = The mean velocity of the overtaken baseflow (DWF)
u_s = The mean wave velocity caused by the influx of storm water
u_b = The mean velocity of the base flow

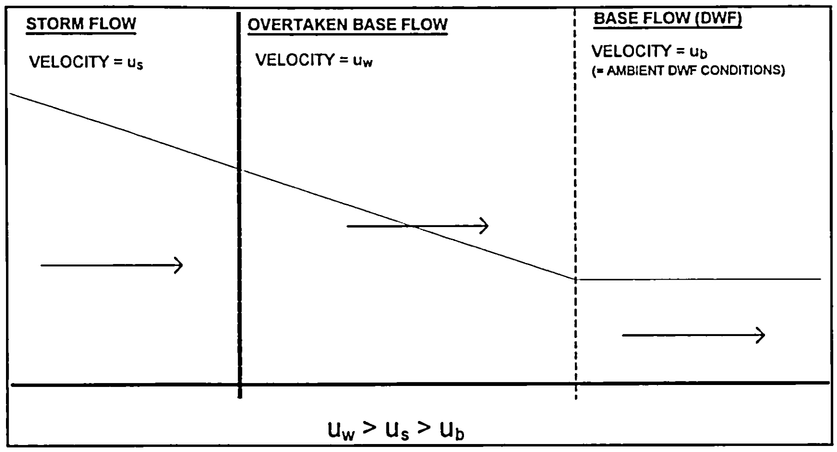


Figure 52 : Idealisation of storm hydrograph
(adapted from Ackers et al., 1968 and Davies, 1990a, 1990b &1996)

The section of steady flow consists of normal DWF, or 'base flow', (with normal suspended and near bed solids sediment transport modes) travelling at ambient DWF velocity. The front part of the storm wave proper will consist of overtaken baseflow, i.e. DWF which is "forced" to travel faster than normal due to the inflow of storm runoff and pressure driving the surge wave. In experiments, using a saline baseflow, Harrison and Holmes (1967) observed negligible dispersion of pseudo storm water mass into the overtaken baseflow. This is idealised by the thick dashed vertical line which separates the 2 zones in the figure. The area between the storm flow and baseflow represents the volume of overtaken base flow. In this overtaken baseflow the velocity conditions are increased, this may then result in the solids moving at the bed being entrained to higher into the flow column, and thus increasing the suspended solids level to above ambient DWF levels, as illustrated in equation 163;

$$TSS_{FLUSH} = TSS_{DWF} + NBS_{DWF} \qquad \text{....163}$$

Where : TSS_{FLUSH} = Solids concentration of the 'flush'
TSS_{DWF} = Ambient DWF solids concentration
NBS_{DWF} = Near bed solids in transport in ambient DWF conditions

The solids in the main storm flow will then consist of baseflow, and solids entrained from transport at the bed. This idealisation is then further developed in Figure 53.

Although these assumptions may appear over simplistic, this approach is the basis for designing storage overflows (Ackers et al., 1968), which was aimed at retaining only the first flush portion of the storm hydrograph. The concept has also been used more recently in the analysis of experiments relating to the overtaken baseflow, by injection of particles by Davies (1990a, 1990b and 1996). Davies found that the concentration of suspended solids in the overtaken baseflow was equal to that in the baseflow for suspended solids transport.

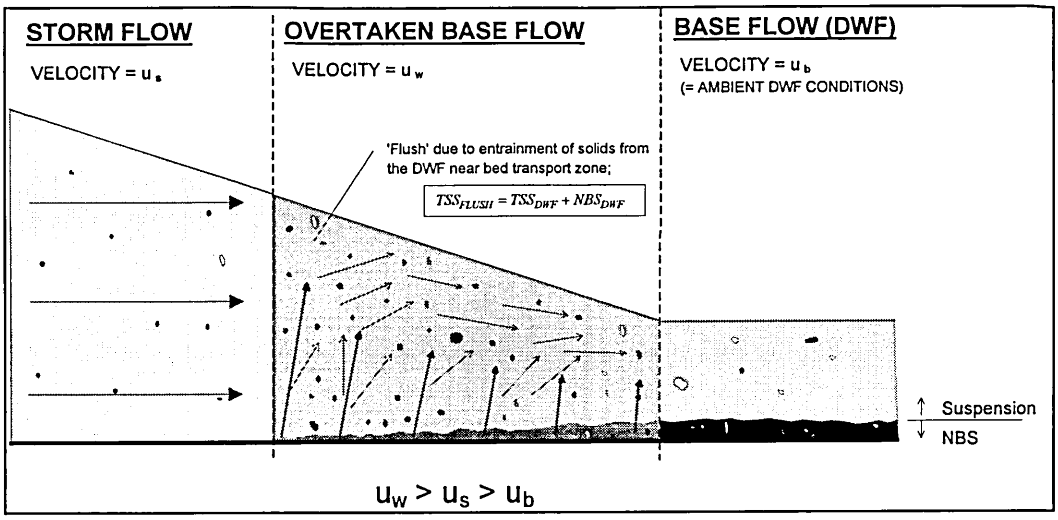


Figure 53 : The role of near bed solids in the first foul flush phenomena

This approach, if valid, can account for the input of the near bed solids to the flush of pollutants observed moving at the front of the storm wave. However, the overtaken baseflow will also contain eroded sediments and slimes, and the approach may be complicated by lateral inputs to the system in a real sewer. Based on the data presented in sections 6.3.1.3.1 'Sediment Transport Rates' and 6.3.1.3.2 'Pollutant Transport Rates' it is possible to estimate the inputs to the first flush if a storm had occurred at the time the samples were obtained. It is also assumed that all of the material moving at the bed during DWF conditions is entrained into the flow. The results are illustrated in Table 56. The data show that if all of the material travelling at the bed were to move into suspension, when the baseflow is 'overtaken', the suspended sediment concentration would increase by 0.5% to 9.05% (average 2.6%), which represents only a modest increase in solids levels. Where the pollution impact of the near bed solids in transport at the bed is considered, however, the effect is more important, as illustrated in Tables 57, 58 and 59 for COD, ammonia and BOD_5 respectively. The pollutant data indicate that the material entrained into the flow may cause the ambient COD and BOD_5 levels to increase by up to 76.8% and 119.4% respectively. Based on these results it can be seen that the role of the near bed solids in terms of first foul flush phenomena is clearly of importance. These results do not take into account the (large) material transported in suspension which cannot be sampled by the small bore samplers.

TABLE 56 : IMPACT OF NEAR BED SOLIDS ON SUSPENDED SOLIDS LEVELS IN A HYPOTHETICAL FIRST FLUSH

Data Set	2	3	4	5	6	7
Measured TSS (mg/l)	186.9	244.7	242.6	263.6	236.0	288.4
$TSS_{FLUSH} = TSS_{DWF} + NBS_{DWF}$ (mg/l)	191.1	248.1	248.7	270.7	243.8	293.3
Increase (%)	2.2	1.4	2.5	2.7	3.3	1.7

Data Set	9	10	11	12	13	14
Measured TSS (mg/l)	270.9	417.3	41.5	42.0	332.0	257.5
$TSS_{FLUSH} = TSS_{DWF} + NBS_{DWF}$ (mg/l)	275.0	419.3	43.1	45.8	335.0	261.0
Increase (%)	1.5	0.5	3.9	9.0	0.9	1.4

Data Set	15	16	18	19	20	21
Measured TSS (mg/l)	36.5	196.0	177.0	184.5	165.0	94.0
$TSS_{FLUSH} = TSS_{DWF} + NBS_{DWF}$ (mg/l)	38.3	203.5	178.1	185.8	171.5	96.4
Increase (%)	4.8	3.8	0.6	0.7	3.9	2.6

Data Set	MIN	AVG	MAX	STD
Measured TSS (mg/l)	36.5	204.2	417.3	100.0
$TSS_{FLUSH} = TSS_{DWF} + NBS_{DWF}$ (mg/l)	38.3	208.2	419.3	100.4
Increase (%)	0.5	2.6	9.0	2.0

TABLE 57 : IMPACT OF NEAR BED SOLIDS ON COD LEVELS IN A HYPOTHETICAL FIRST FLUSH

Data Set	2	3	4	5	6	7
Measured TSS COD (mg/l)	747.0	737.5	677.8	663.9	705.9	679.0
$COD_{FLUSH} = COD_{TSS} + COD_{NBS}$ (mg/l)	785.4	791.5	742.1	729.8	775.0	747.0
Increase (%)	5.1	7.3	9.5	9.9	9.8	10.0

Data Set	10	11	12	13	14	15
Measured TSS COD (mg/l)	834.8	230.5	256.2	744.5	587.4	148.5
$COD_{FLUSH} = COD_{TSS} + COD_{NBS}$ (mg/l)	871.0	242.1	308.9	777.0	618.9	262.5
Increase (%)	4.3	5.0	20.6	4.4	5.4	76.8

Data Set	16	MIN	AVG	MAX	STD
Measured TSS COD (mg/l)	556.5	148.5	582.3	834.8	215.0
$COD_{FLUSH} = COD_{TSS} + COD_{NBS}$ (mg/l)	691.4	242.1	641.8	871.0	210.8
Increase (%)	24.2	4.3	14.8	76.8	18.8

These data show that the near bed solids mode of transport can have a significant impact on the pollution impact of first foul flushes associated with storm flows. However the data also indicates that although the pollutant concentration may increase by up to 77% and 119% for COD and BOD_5 respectively the solids in suspension only increases by up to 9%. This indicates that in the Dundee interceptor, and possibly further afield, the increased solids levels in the first flush originates from sources other than the near bed solids mode of transport (i.e. sewer sediments). Additionally, the high pollution concentrations are sourced, at least in part, from the material in transport near the bed. Although, it should be remembered, the type of material in transport near the bed at Study Site 3 is not found in other sewers (e.g. Study Site 1, Lin et al., 1993a & b and Bertrand-Krajewski et al., 1995) where the material was found to be coarser and predominately inorganic.

TABLE 58 : IMPACT OF NEAR BED SOLIDS ON AMMONIA LEVELS IN A HYPOTHETICAL FIRST FLUSH

Data Set	2	4	5	6	7	10
Measured TSS NH4 (mg/l)	11.20	20.50	22.10	7.40	15.30	14.20
$NH4_{FLUSH} = NH4_{TSS} + NH4_{NBS}$ (mg/l)	11.24	20.62	22.18	7.47	15.37	14.25
Increase (%)	0.40	0.60	0.35	0.95	0.48	0.37

Data Set	11	12	13	14	15	16
Measured TSS NH4 (mg/l)	8.65	9.25	27.50	28.35	9.30	25.50
$NH4_{FLUSH} = NH4_{TSS} + NH4_{NBS}$ (mg/l)	8.67	9.37	27.58	28.44	9.43	25.72
Increase (%)	0.28	1.33	0.29	0.32	1.35	0.87

Data Set	MIN	AVG	MAX	STD
Measured TSS NH4 (mg/l)	7.40	16.60	28.35	7.49
$NH4_{FLUSH} = NH4_{TSS} + NH4_{NBS}$ (mg/l)	7.47	16.70	28.44	7.51
Increase (%)	0.28	0.63	1.35	0.38

TABLE 59 : IMPACT OF NEAR BED SOLIDS ON BOD_5 LEVELS IN A HYPOTHETICAL FIRST FLUSH

Data Set	2	5	6	7	10	11
Measured TSS BOD_5 (mg/l)	481.7	321.1	492.7	577.9	632.2	67.3
$BOD_{FLUSH} = BOD_{TSS} + BOD_{NBS}$ (mg/l)	507.2	377.5	549.7	618.0	661.4	71.5
Increase (%)	5.3	17.6	11.6	6.9	4.6	6.3

Data Set	12	13	14	15	16
Measured TSS BOD_5 (mg/l)	54.8	444.6	371.2	38.4	388.1
$BOD_{FLUSH} = BOD_{TSS} + BOD_{NBS}$ (mg/l)	120.2	493.6	418.3	84.1	474.7
Increase (%)	119.4	11.0	12.7	119.1	22.3

Data Set	MIN	AVG	MAX	STD
Measured TSS BOD_5 (mg/l)	38.4	351.8	632.2	201.2
$BOD_{FLUSH} = BOD_{TSS} + BOD_{NBS}$ (mg/l)	71.5	397.8	661.4	202.4
Increase (%)	4.6	30.6	119.4	42.1

6.6 Conclusions

- Three study sites were established as part of the project described here, each of which had significantly different hydraulic conditions.

- Considerable differences in the particle size distribution of the inorganic fraction material being transported at the bed were observed between the data collected at all three sites. A variation in the particle size distribution was observed, and was hypothesised as being dependent on ambient hydraulic conditions, although factors such as upstream conditions may also be important.

- The trunk sewer near bed solids were characterised as being predominately coarse and of low organic content when compared with the samples collected from the two interceptor sewer sites. Additionally, significant variations were also observed between samples obtained at the same site (i.e. between 8.2 and 91.2% at study site 3).

- At Study Site 3 there was little variation in the bulk density of the material in transport. This was due to the high moisture and organic content of the material. A tentative relationship was observed from the data collected at Study Site 3 which related the dry density of the material in transport to the ambient velocity conditions, however this relationship requires additional data before it can be applied.

- The measured settling velocity of the material sampled moving near the bed was found to be higher than that of the overlying sewage concurrently sampled.

- The pollutant concentration of the material moving near the bed was found to be greater than that measured for the suspended solids mode of transport and for deposited sediments. A site specific relationship was obtained which related the ammonia concentrations in the near bed solids to hydraulic conditions and inputs to the system.

- Considerable variations in the near bed solids transport rates were noted between the data collected at each of the sites, and between individual samples obtained from each of the sites.

- The transport rates of specific pollutants were also considered. The data indicated that the near bed mode of transport conveyed a concentrated BOD_5 and COD load, when compared with suspended solids transport.

- Based on multi-depth samples obtained using small bore samplers, pollutant concentration variation with depth was observed, with the highest concentration being found at the bed.

- Based on the observations made at each of the sites, and the data collected, the influence the material in transport near the bed has on the intensity of first foul flush was examined. It was hypothesised that whilst the near bed mode of transport represents only a moderate proportion of the total solids in transport, the solids, and associated pollutants, would have potential to contribute significantly to the pollutant concentration of first foul flush events. This finding will be further investigated in the next chapter 'Model Development'.

Chapter 7 : Model Development

7.1 Introduction

In the preceding chapter the results from each of the field sites were discussed in general. In this chapter the sediment transport rate data are analysed in detail, in an attempt to relate this to other parameters.

The initial aim of the data analysis was to obtain a predictive relationship which could be used to estimate sediment transport near the bed at any point in a sewer system, within a reasonable degree of accuracy, based on parameters which may be readily measured or determined. For the purposes of this study the degree of accuracy which is sought from any predictive model was as defined below, which is common to the sediment transport field, both in sewers and fluvial hydraulics (White et al. 1975);

$$50\% < \frac{Calculated\,Transport\ Rate}{Measured\,Transport\ Rate} < 200\%$$

Initially, data obtained at each study site were analysed independently of that collected at the other study sites before being coalesced.

7.2 Study Site 1 : Trunk Sewer

Due to the prototype nature of the work undertaken at Study Site 1 the sediment transport rate data are not robust enough to be considered alone. The reasons for this were dealt with in the preceding chapter (section 6.3.1.3.1 "Sediment Transport Rates").

7.3 Study Site 2 : Interceptor Sewer, Head of System

At this site the data collected consisted of 5 DWF data sets. The limited quantitative nature of the data meant that, when considered alone, they are not sufficient to generate an independent transport equation, and data analysis is restricted, primarily, to application of existing laboratory based 'bed-load' transport equations.

As a sediment bed formed along the invert of the test section used for data collection in this part of the project, only laboratory models based on sediment transport experiments over sediment beds (loose or rigid) were considered as candidates for application to the field data. A review of literature (section 4.3 "Transport Over a Sediment Bed") based on work undertaken in this field indicates that laboratory based models which have been developed to predict sediment transport in sewers have been based on material of restricted particle size, and of relatively high specific gravity (>2.50). This is in sharp contrast with the predominately highly organic, and diverse, material in transport near the bed in sewers in the Dundee sewerage system, and wider afield (Verbanck, 1995, Ristenpart et al., 1995, and Lin et al., 1993a & 1993b).

7.3.1 Inorganic Transport Rates

To overcome this apparent dichotomy, in the application of the laboratory based models to the field data from Study Site 2, the material in transport at the bed was initially considered as being made up of two distinct components; organics and inorganics. It is principally the organic fraction of the material in transport at the bed in sewers which is the cause of the high pollutant load, and aesthetic pollution the problems associated with this material. It is, therefore, the prediction of the transport of this component which is the most important factor. However, it is the inorganic fraction of the material which conforms closest to the material used as a surrogate sediment in laboratory studies (i.e. silts, sands and gravels). Based on this, in the first instance, the application of the sediment transport ("bed-load") models was restricted to the inorganic fraction only. The models chosen for application to the field data are illustrated in equations 164, 165, 166, 167 and 168:

Ackers (1991)

$$C_v = J\left(W_e\frac{R}{A}\right)^a\left(\frac{d}{R}\right)^\beta \lambda_c^\gamma\left(\frac{V}{\left[g(s-1)R\right]^{-1/2}} - K\lambda_c^\delta\left(\frac{d}{R}\right)^\varepsilon\right)^m \qquad ...164$$

Nalluri and Alverez (1992)

$$C_v = 1.85\times10^{-2}\lambda^{0.590}\left(\frac{d_{50}}{R_b}\right)^{0.419}\left(\frac{V^2}{g(s-1)R_b}\right)^{1.56} \qquad ...165$$

Ab. Ghani (1993)

$$C_v = 0.355\left(\frac{W_b}{y_o}\right)^{1.12}\left(\frac{D}{d_{50}}\right)\lambda_c^{1.94}\left(\frac{V^2}{g(s-1)D}\right)^{3.12} \qquad ...166$$

May (1993 & 1994)

$$C_v = \eta\left(\frac{W_b}{D}\right)\left(\frac{D^2}{A}\right)\left(\frac{\theta\lambda_g V^2}{8g(s-1)D}\right) \qquad ...167$$

Perrusquìa & Nalluri (1995)

$$\Phi_b = 0.0143\Theta_g^{2.2}D_*^{0.38}\left(\frac{d_{50}}{y}\right)^{-1.11}\left(\frac{B}{y}\right)^{0.78} \qquad ...168$$

Table 60 compares the measured and predicted near bed inorganic solids transport rates using each of the DWF data sets for Study Site 2.

TABLE 60 : EVALUATION RESULTS - STUDY SITE 2
INORGANIC FRACTION ONLY

	29.04.93	13.05.93	19.05.93.	25.05.93.	27.05.93
Measured Transport Rate (g/s)	0.387	0.336	0.800	0.242	0.593
Measured C_V (ppm)	1.509	1.768	2.081	1.609	2.623
Predicted Sediment Transport Rates (g/s)					
Ackers (1991)	-19.56	-23.241	-14.257	-14.784	-12.044
Nalluri & Alverez (1992)	0.216	0.150	0.188	0.380	0.459
Ab. Ghani (1993)	1.16×10^{-3}	4.23×10^{-4}	1.66×10^{-3}	1.73×10^{-3}	2.23×10^{-3}
May (1993)	0.257	0.041	0.173	0.756	1.090
May (1994)	0.193	0.030	0.129	0.567	0.817
Perrusquía & Nalluri (1995)	4.412	1.293	7.788	3.675	4.696
Model Accuracy : $\left(\dfrac{\text{Calculated Transport Rate}}{\text{Measured Transport Rate}}\right)\times 100\%$					
Ackers (1991)	-5048	-6919	-1783	-6116	-2029
Nalluri & Alverez (1992)	55.7	44.6	23.5	157.0	77.3
Ab. Ghani (1993)	0.30	0.13	0.21	0.72	0.38
May (1993)	66.3	12.1	21.6	312.8	183.6
May (1994)	49.7	9.1	16.2	234.6	137.7
Perrusquía & Nalluri (1995)	1138.9	384.9	973.7	15202	791.2

As the table shows, none of the relationships operated consistently within the stated aims of 50% to 200% of the measured transport rate, although some do perform better than expected, notably; Nalluri & Alvarez (1992), May (1993) and May (1994). The remaining models either over-predict or under-predict the transport rate observed in the field. The inability of the models to provide more accurate results may be due to one, or more, of several factors:

- Sewer Size

  The sewer in which Study 2 is based is of a large diameter (1750 × 1625mm) which is in contrast with the relatively small pipes used in laboratory studies.
- Relative Depth

  The relative depth (y_0/D) does not vary to any great extent during the DWF conditions observed at the site, and in addition it was always lower than 25% of the pipe diameter (18.1 - 20.1% - essentially constant).
- Bed Characteristics

  The sediment beds used in laboratory tests are, predominately, constructed from single size sands. This is in contrast with the diverse material observed from the sediment bed along the invert of the test rig used at Study Site 2. The particle size distribution of the inorganic fraction of the sediment bed observed at Study Site 2 is illustrated in Figure 54:

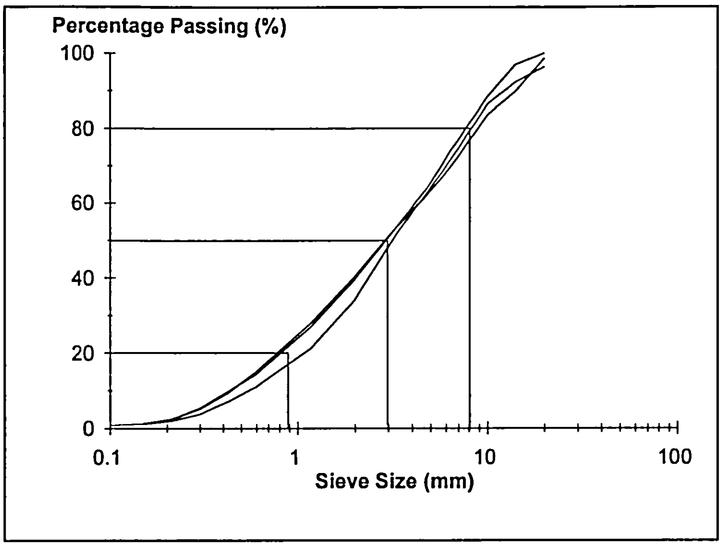


Figure 54 : Study 2 sediment bed inorganic particle size distribution

- Sediment Concentrations
  The majority of the work undertaken in the laboratory is at the transport capacity of the flow, and volumetric sediment transport concentrations were typically much higher than those observed in the field. Sediment transport concentrations in sewerage systems do not necessarily move at the transport capacity of the flow, and are largely dependent on inputs to the system.
- Flow Conditions
  The uniform flow conditions on which laboratory based predictive models are constructed are somewhat different to the flow conditions experienced at the field site.

7.3.2 Total Solids Transport Rates

To further evaluate the models selected, an attempt was made to modify their performance by applying scalar coefficients. The modification of the existing models was restricted to the application of coefficients due to the limited range of data available. Table 61 and Figure 55 compare the measured and predicted near bed inorganic solids transport rates, for the DWF data sets from Study Site 2 using the modified relationships. The table gives identical results for the models obtained by May (1993) and May (1994). This is due to the only difference between the relationships being the determination of the coefficient η. For the Study Site 2 data, the relationships used for determination of η for May (1993) and May (1994) are illustrated in equations 169 and 170. The use of this relationship on the Study Site 2 data effectively means that the results from May (1993) will always be 33% higher

(1.6÷1.2) than those obtained using May (1994), and the application of constants to all the results cancels this out. Table 62 shows the coefficients used.

$$\eta = 1.6 \times (F_s - 0.1) \qquad \text{....169}$$

$$\eta = 1.2 \times (F_s - 0.1) \qquad \text{....170}$$

TABLE 61 : EVALUATION RESULTS - MODIFIED RELATIONSHIPS (INORGANIC TRANSPORT ONLY)

	29.04.93	13.05.93	19.05.93.	25.05.93.	27.05.93
Measured Transport Rate (g/s)	0.387	0.336	0.800	0.242	0.593
Measured C_V (ppm)	1.509	1.768	2.081	1.609	2.623
Modified Model Accuracy : $\left(\frac{\text{Calculated Transport Rate}}{\text{Measured Transport Rate}}\right) \times 100\%$					
Ackers (1991)	115.2	158.0	40.71	139.6	46.35
Nalluri & Alverez (1992)	77.78	62.22	32.76	219.3	107.9
Ab. Ghani (1993)	86.64	36.51	60.20	207.7	108.0
May (1993)	55.60	10.13	18.09	262.3	153.9
May (1994)	55.60	10.13	18.09	262.3	153.9
Perrusquía & Nalluri (1995)	118.4	40.02	101.1	158.1	82.2

TABLE 62 : COEFFICIENTS FOR THE MODIFIED RELATIONSHIPS

Researcher	Coefficient
Ackers (1991)	-2.284×10^{-2}
Nalluri & Alverez (1992)	1.397
Ab. Ghani (1993)	290.1
May (1993)	0.838
May (1994)	1.117
Perrusquía & Nalluri (1995)	0.104

As the table illustrates, the application of coefficients to the existing models improves their performance considerably, although none of the relationships consistently produce a predicted near bed transport rate within the required range (50% to 200%) for all the data sets. Analysis of the results indicate that the relationship which performs best is the modified form of that obtained by Perrusquía & Nalluri (1995). However the results from the data set collected on 13.05.93 are some 10% outside the range sought. It is hypothesised that this may be due to the time in the diurnal period at which this data set was collected, i.e. at the onset of the morning peak in flow velocity and discharge. When, it is hypothesised, some of the material which has deposited during the night time flow recession may erode due to the slight increase in bed shear stress associated with the onset of the morning peak in the DWF hydrograph. The relationship cannot model inputs to the system, so it therefore does not account for the hypothesised erosion.

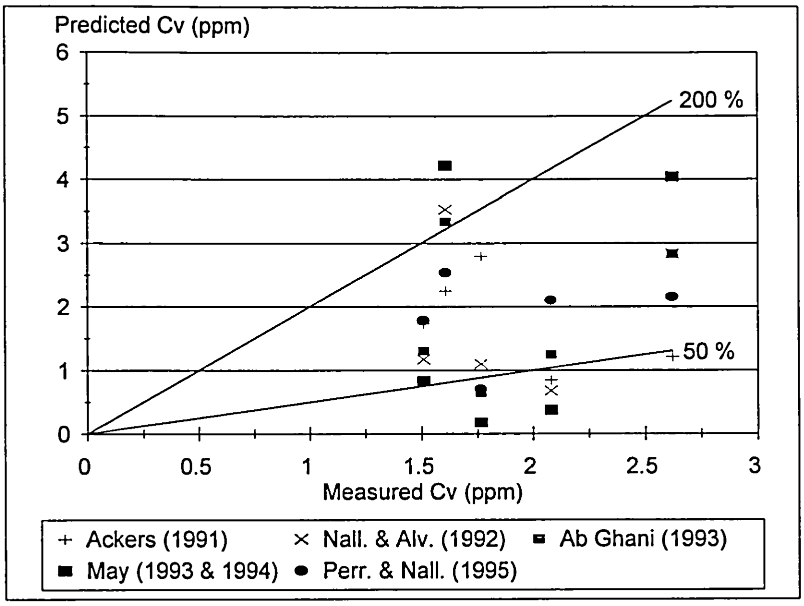


Figure 55 : Evaluation results - modified relationships (inorganic transport only)

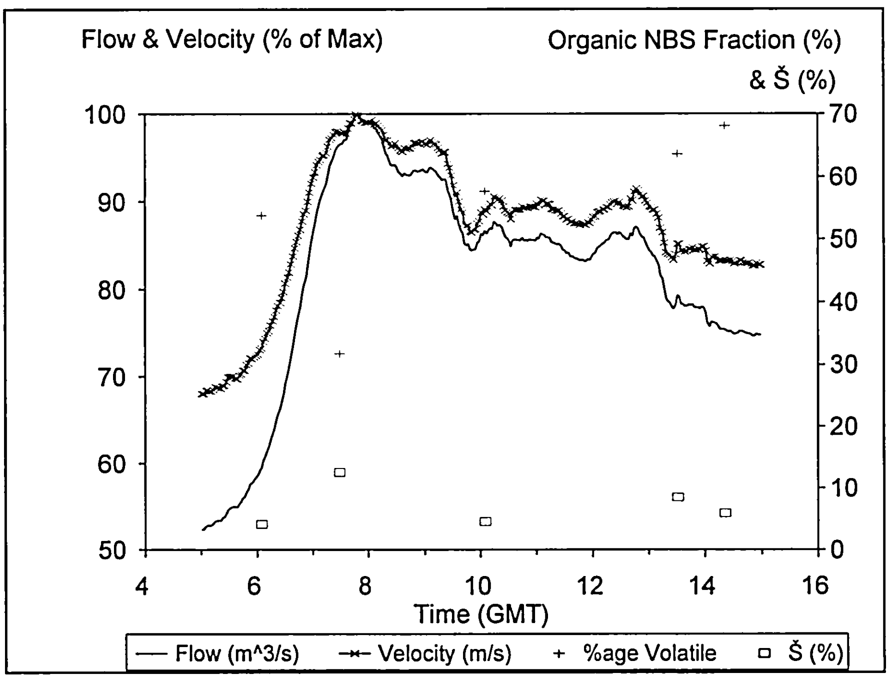


Figure 56 : Variation in characteristics of material transported at the bed - Study 2#

The data collected have shown that the nature of the material collected in Dundee varies throughout the day (Ashley et al., 1993 and Arthur & Ashley, 1994), this being due to changes in domestic and commercial inputs and ambient velocity

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Š is defined in section 6.3.1.3.1 "Sediment Transport Rates" as:

$$\breve{S} = \frac{\text{Mass of Solids Moving at the Bed}}{\text{Mass of Solids Moving at the Bed \& in Suspension}} \times 100\%$$

conditions. The data are illustrated in Figure 56, which shows that as the flow conditions increase, the organic content of the material in transport near the bed may decrease, and the proportion of the total transported load (by dry mass) which travels at the bed (Š) increases. However the data are limited, and this observation is only tentative.

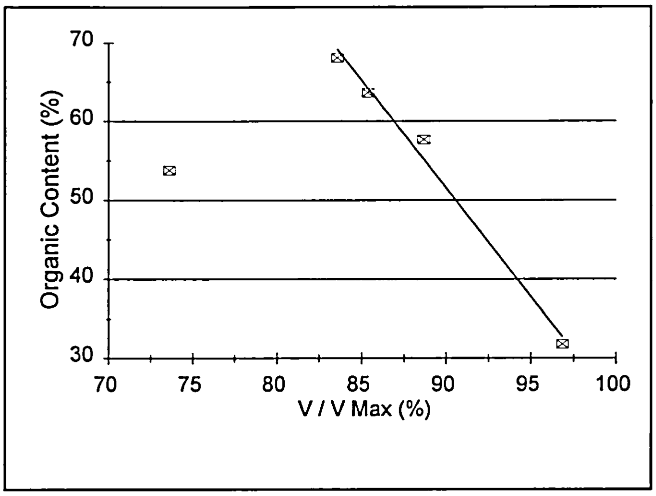

Figure 57 : Organic content variation

Further analysis of the mass of data collected at Study Site 2 shows that when the volatile content of the material sampled moving at the bed is compared with the velocity at the time of day at which the samples were collected, there is a suggestion that the two parameters may be related (Figure 57). The data point which does not conform was that collected at the onset of the morning peak in flows, where a limited amount of erosion of material which has deposited during the nocturnal flow recession may take place. The errant data set (13.05.93) appears to indicate that the main material to be eroded was inorganic in nature (when dry weight is considered). Velocity is represented by V/V_{max} at the time the sample was retrieved using anaverage DWF profile in the figures as this removes any influence time related factors may have, such as ADWP (i.e. the velocity of the flow in the sewer is related to inputs to the system).

As the modified relationship under-predicts the inorganic transport rate, this supports the hypothesis, to some extent, that inorganics are the main material to be eroded during the morning peak. The modified form of the relationship is shown in equation 171. It can be seen that if the modified Perrusquía and Nalluri (1995) relationship is used in conjunction with the relationship between the organic content of the sampled material and the ambient velocity conditions, a methodology may be formed which can be used to predict the total amount of material in transport (organic + inorganic). The modified Perrusquía and Nalluri (1995) may first be used to estimate the inorganic sediment transport rate. The relationship between the organic content on the near bed solids and V/V_{max} may then be used to estimate the organic fraction. The respective masses than may be summed to obtain the total mass in transport.

$$\Phi_b = 1.4872\times10^{-3}\Theta_g^{2.2}D_*^{2.6}\left(\frac{d_{50}}{y}\right)^{-1.11}\left(\frac{B}{y}\right)^{0.78} \qquad ...171$$

The next step in the evaluation of the laboratory models was to attempt to apply them to the total mass of material in transport at the bed. Before this could be undertaken, however, consideration had to be given to two factors;

1. Material Particle Size

Due to the diverse nature of the material moving near the bed in sewers it proved difficult to obtain an accurate estimation of the particle sizes of the material as a whole, and only the size of the inorganic particles could be determined with any accuracy (see section 6.3.1.1.1 "Particle Size Distribution"). However, all the laboratory based sediment transport methodologies are highly dependent on size of the particles in transport. To overcome this problem the inorganic particle size was used in the anticipation that the equations would respond to relative differences in particle sizes, rather than absolute variations. Although this assumption may be unsophisticated, it is necessary due to limited quantitative nature of the data set.

2. Material Bulk Density

All the predictive relationships available use a submerged specific gravity parameter ("*s-1*") to some extent. In the laboratory, where the specific gravity of the material used is relatively high, this may be acceptable, however in the field this causes some problems due to the much lower densities under consideration (average = 1043.0 - 1119.9 kg/m^3 for Study 2). Any small differences in the bulk density of the material are greatly exaggerated, more so than that for the sediments used in the laboratory when the submerged specific gravity is readily determined. Additionally, the bulk density observed in the field is well outside the range used in the laboratory. To overcome this problem two approaches were investigated;

    1. Substitute "*s-1*" with "*2.65 - 1*"
    2. Substitute "*s-1*" with "*s*".

As with the prediction of the inorganic transport concentration, none of the relationships performed within the range sought, however, once scalar coefficients were applied to each of the relationships some of the results improved. The results of the evaluation using "*s-1*" substituted with "*2.65 - 1*" are illustrated in Table 63 and Figure 58. The coefficients used are given in Table 64.

As the results of this part of the evaluation show, the laboratory based relationships perform better, after coefficients have been applied, when the material is considered as a whole rather than the inorganic fraction alone. As with the earlier evaluation, the model developed by Perrusquía & Nalluri (1995) was found to perform best, after modification. The modified relationship is shown in equation 172;

$$\Phi_b = 3.7609 \times 10^{-3} \Theta_g^{2.2} D_*^{2.6} \left(\frac{d_{50}}{y}\right)^{-1.11} \left(\frac{B}{y}\right)^{0.78} \quad ...172$$

Where Φ_b and Θ_g are now defined as illustrated in equations 173 and 174.

$$\Phi_b = \left(C_v VR \Big/ \left[g(2.65-1)(d_{50})^{3.0} \right]^{0.5} \right) \quad ...173$$

$$\Theta_g = \left(\left[\tau_b \big/ \rho \right] \Big/ \left[g(2.65-1)(d_{50}) \right] \right) \quad ...174$$

TABLE 63 : EVALUATION RESULTS FOR TOTAL SOLIDS TRANSPORTED AT THE BED FOR STUDY SITE 2

	29.04.93	13.05.93	19.05.93.	25.05.93.	27.05.93
Measured Transport Rate (g/s)	1.160	0.683	1.428	0.802	1.420
Measured C_V (ppm)	13.03	10.35	16.04	9.78	15.64
Modified Model Accuracy : $\left(\frac{\textit{Calculated}\ \text{Transport Rate}}{\textit{Measured}\ \text{Transport Rate}}\right) \times 100\%$					
Ackers (1991)	93.03	193.7	56.88	105.0	48.32
Nalluri & Alverez (1992)	69.78	82.15	49.29	177.6	121.2
Ab. Ghani (1993)	76.65	47.54	89.32	165.8	120.7
May (1993)	52.43	14.05	28.61	223.3	181.7
May (1994)	52.43	14.05	28.61	223.3	181.7
Perrusquía & Nalluri (1995)	99.88	49.69	143.2	120.4	86.84

TABLE 64 : COEFFICIENTS FOR THE MODIFIED RELATIONSHIPS FOR PREDICTION OF TOTAL SOLIDS IN TRANSPORT NEAR THE BED AT STUDY SITE 2

Researcher	Coefficient
Ackers (1991)	-5.69×10^{-2}
Nalluri & Alverez (1992)	3.751
Ab. Ghani (1993)	769.23
May (1993)	2.367
May (1994)	3.157
Perrusquía & Nalluri (1995)	0.263

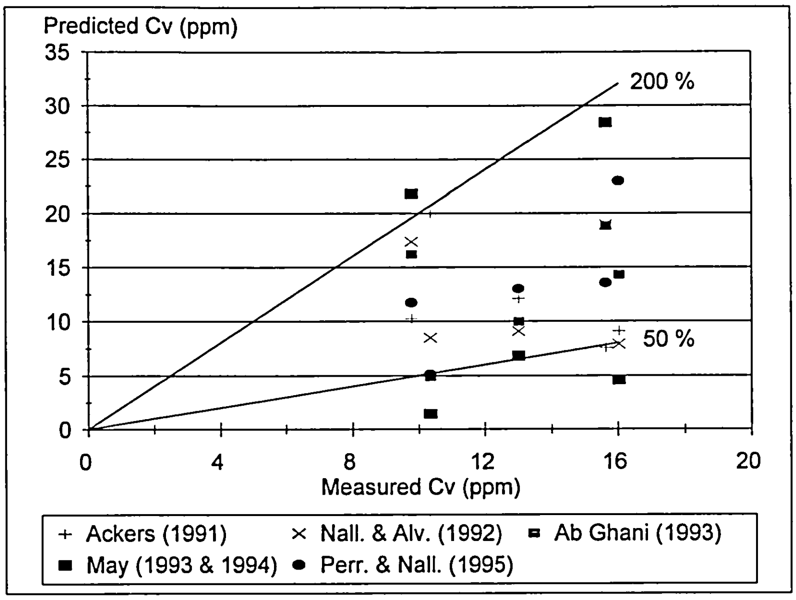

Figure 58 : Evaluation results - modified relationships
(Total mass transport)

The final stage in the evaluation of the laboratory relationships was to substitute "*s-1*" with "*s*". As with the prediction of the inorganic transport concentration none of the relationships performed within the range sought, however, once coefficients were applied to each of the relationships some of the results improved. The results of the evaluation using "*s-1*" substituted with "*s*" are illustrated in Table 65 and Figure 59. The coefficients used are given in Table 66.

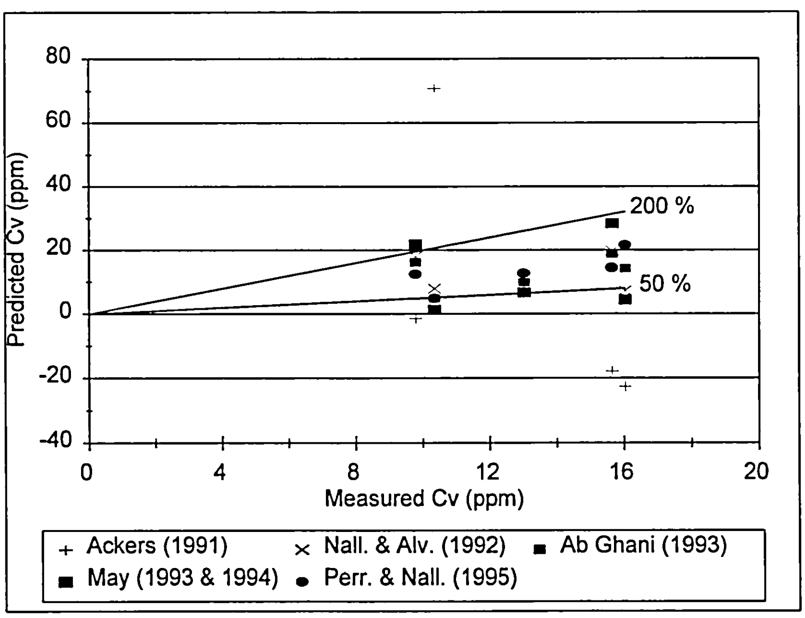

Figure 59 : Evaluation results - modified relationships
(Total mass transport)

TABLE 65 : EVALUATION RESULTS FOR TOTAL MASS TRANSPORTED NEAR THE BED AT STUDY SITE 2

	29.04.93	13.05.93	19.05.93.	25.05.93.	27.05.93
Measured Transport Rate (g/s) Measured C_V (ppm)	1.160 13.03	0.683 10.35	1.428 16.04	0.802 9.78	1.420 15.64
Modified Model Accuracy : $\left(\frac{\textit{Calculated}\text{ Transport Rate}}{\textit{Measured}\text{ Transport Rate}}\right)\times 100\%$					
Ackers (1991)	82.21	684.8	-140.8	-13.58	-113.6
Nalluri & Alverez (1992)	66.55	76.84	45.53	184.6	126.6
Ab. Ghani (1993)	76.65	47.54	89.32	165.8	120.7
May (1993)	52.19	14.05	28.61	223.3	181.7
May (1994)	52.19	14.05	28.61	223.3	181.7
Perrusquía & Nalluri (1995)	97.27	47.45	134.75	127.8	92.74

TABLE 66 : COEFFICIENTS FOR THE MODIFIED RELATIONSHIPS FOR PREDICTION OF TOTAL MASS IN TRANSPORT NEAR THE BED AT STUDY SITE 2

Researcher	Coefficient
Ackers (1991)	-0.256
Nalluri & Alverez (1992)	1.917
Ab. Ghani (1993)	201.4
May (1993)	0.779
May (1994)	1.038
Perrusquía & Nalluri (1995)	0.136

The results of this part of the evaluation show the laboratory based relationships perform better, after coefficients have been applied, when the material is considered as a whole rather than the inorganic fraction alone. As with the earlier evaluation, it is the model developed by Perrusquía & Nalluri (1995) which performs better than the others, after modification. The modified relationship is shown in equation 175;

$$\Phi_b = 1.95 \times 10^{-3}\Theta_g^{2.6}\left(\frac{d_{50}}{y}\right)^{-0.79}\left(\frac{B}{y}\right)^{0.67} \qquad ...175$$

Where Φ_b and Θ_g are now defined as illustrated in equation 176 and 177.

$$\Phi_b = \left(C_v VR \Big/ \left[g(s)(d_{50})^{3.0}\right]^{0.5}\right) \qquad ...176$$

$$\Theta_g = \left(\left[\tau_b/\rho\right] \Big/ \left[g(s)(d_{50})\right]\right) \qquad ...177$$

7.3.3 Study Site 2 Conclusions

The data obtained from Study 2 are relatively limited and any results obtained are, as a consequence, inferential. However, some trends have been shown, and it is possible to draw the following conclusions.

- The organic content of the material being transported near the bed changes throughout the day. This is likely to be a function both of inputs to the system, and also due to some of the organic material moving into the suspended mode of transport due to increased velocity conditions at certain times in the DWF hydrograph.
- Application of existing laboratory generated relationships is not straight-forward. However, tentative relationships have been obtained for the prediction of inorganic and total near bed solids transport concentrations. The relationships are so far only site specific due to the large amounts of data required in their formulation. However, using the modified relationships obtained, in conjunction with the relationship between organic content of the material moving at the bed and the ambient velocity conditions, it is possible to estimate the rate of transport of material along the bed at this part of the interceptor sewer in Dundee during DWF conditions.

7.4 Study Site 3 : Downstream Interceptor Site

The main data collected over the duration of this project have been obtained from Study Site 3, which is sited in the Dundee interceptor sewer. The main emphasis of data collected at this site has been on the material moving at the bed in the test rig, although other data were collected.

Over the ten month duration of data collection at Study Site 3, a total of 21 DWF data sets were collected, directly relating to the movement of solids along the bed of the test section. The amount of data collected were deemed sufficient to generate an independent near bed solids transport model which could be applied to the field site, and conceivably further afield. Figure 60 shows the methodology used to obtain a model. As with the work undertaken at Study Site 2, the aim of the analysis was to obtain a predictive relationship which could be used to estimate sediment transport at any point in a sewer system, within a reasonable degree of accuracy, based on parameters which may be readily measured or determined.

7.4.1 Laboratory Based Models

The first stage in the analysis of the data collected at Study Site 3 was to apply laboratory generated 'bed-load' transport models, this had 4 main purposes:

1. If any of the existing laboratory based models perform well enough it may not be necessary to perform any further analysis of the field data.
2. It may be possible to modify one of the existing models so that they perform well enough on the field data that no further analysis will be required.

3. The application of these models may give an indication of which parameters, or dimensionless groups, are important and should be used if further analysis is required.
4. Currently, the laboratory models are the only tools available to engineers and system operators to predict the movement of material at the bed in combined, and separate, sewer systems and it is important to evaluate their performance using field data.

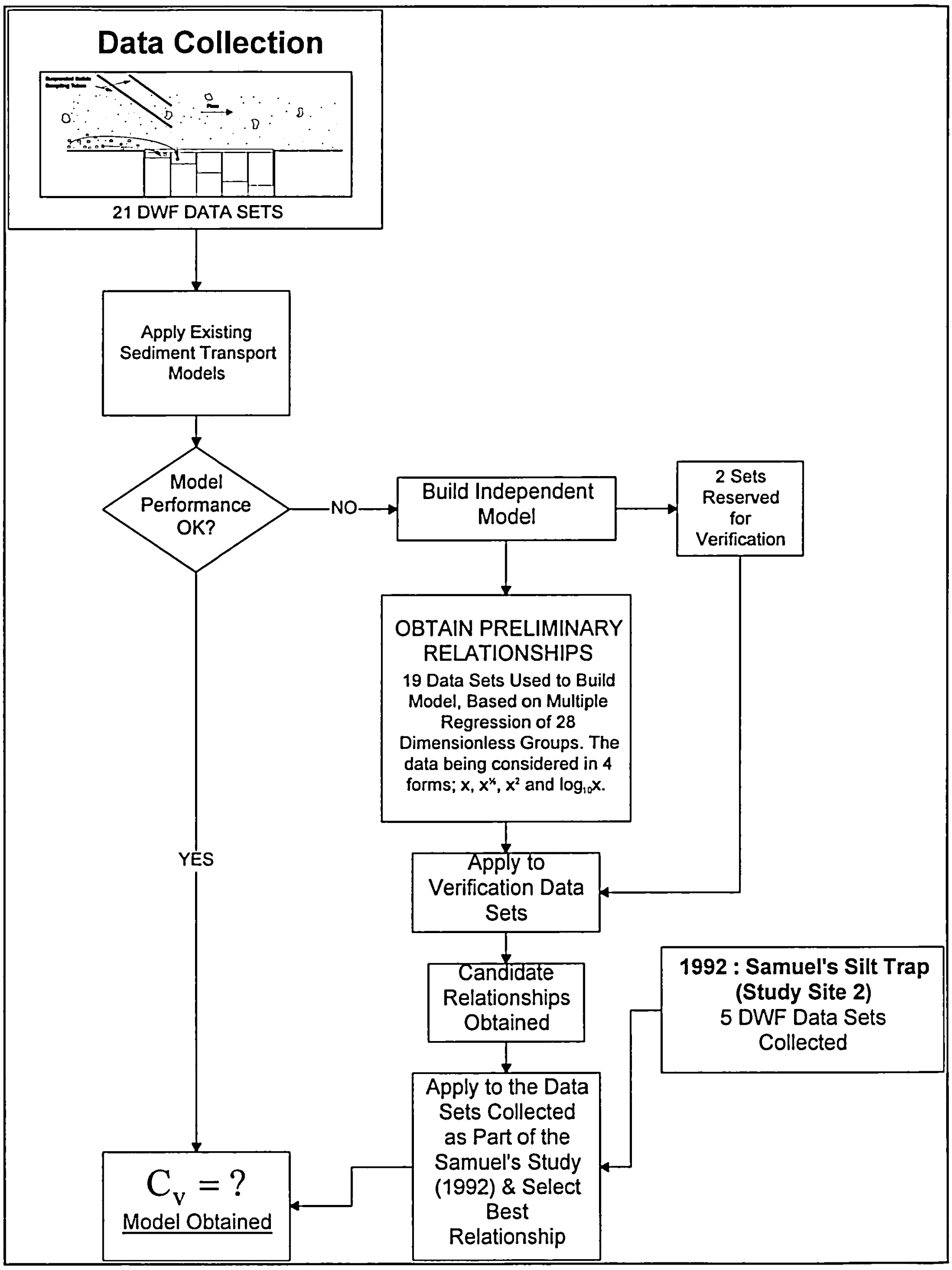

Figure 60 : Flow diagram - Model development for Study Site 2

Over the duration of Study 3 no permanent sediment bed could be encouraged to form (this is discussed in section 5.3.3.1 "Test Procedure and Instrumentation"), this condition meant that the models tested on the Study Site 2 data could not be used, as these rely on a sediment bed being present for determination of the width of the bed over which the transport of sediment takes place. The models which were applied to the Study 3 data were those obtained from experiments undertaken for transport at the limit of deposition in laboratory studies. A review of literature (Section 4.3.2 "Transport at Limit of Deposition in Pipes") concerning the development of laboratory based models at the limit of deposition indicated that, as with transport over deposited beds, the work is based on transport of material of restricted particle size and relatively high specific gravity. In the analysis of the Study Site 2 data this was overcome by, initially, segregating the sampled material into organic and inorganic fractions. However, due to the very high organic and moisture content levels in much of the samples obtained at Study Site 3 (up to 91.2% and 1900.3%[#] respectively) and the small inorganic particle sizes, the results of the particle size distribution analysis of the samples may be influenced, adversely, by the ashed residue of the volatile fraction of the material (this is discussed in section 6.3.1.1.1 "Particle Size Distribution"). Based on this it was decided to analyse the material in transport at this site as a whole (organic + inorganic), rather than in separate fractions.

The proposed clean pipe limit of deposition models chosen for application to the data collected at Study Site 3 are illustrated in equations 178, 179, 180 and 181;

Nalluri & Ab. Ghani(1993).

$$C_v = 4.52 \times 10^{-3}\left(\frac{d_{50}}{R}\right)^{0.045} D_{gr}^{0.545}\lambda_c^{1.18}\left(\frac{V_L^2}{g(s-1)R}\right)^{2.27} \qquad \text{....178}$$

Ab. Ghani (1993)

$$C_v = 4.79 \times 10^{-3}\left(\frac{d_{50}}{R}\right)^{0.146} D_{gr}^{0.448}\lambda_o^{1.00}\left(\frac{V_L^2}{g(s-1)R}\right)^{2.43} \qquad \text{...179}$$

Nalluri, Ab. Ghani & El-Zaemey (1994)

$$C_v = 1.29 \times 10^{-3}\left(\frac{y}{D}\right)^{0.627}\left(\frac{d_{50}}{D}\right)^{0.421} \lambda_o^{-0.819}\left(\frac{V_L^2}{g(s-1)y}\right)^{3} \qquad \text{...180}$$

[#] The moisture content, *m*, is calculated using the standard geotechnics methodology (BS1377):

$$m = \left(\text{Mass of Water} \big/ \text{Mass of Solids}\right) \times 100\%$$

May (1994)

$$C_v = 3.03 \times 10^{-2}\left(\frac{D^2}{A}\right)\left(\frac{d}{D}\right)^{0.6}\left(1-\frac{V_t}{V}\right)^4\left(\frac{V^2}{g(s-1)D}\right)^{1.5} \qquad ...181$$

The development of these equations is discussed in section 4.3.2 "Transport at Limit of Deposition in Pipes".

Before the evaluation of the laboratory models could be undertaken 2 problems had to be overcome:

1. Material Particle Size

Due to the nature of the material moving near the bed at this site it proved difficult to obtain an accurate estimate of the mean particle size of the samples collected, and only a crude estimation could be made. However, all laboratory work undertaken at the limit of deposition is highly dependent on an accurate determination of the particle characteristics, and in particular the mean particle size (d_{50}). To overcome this problem a method was obtained which could be used to gain an estimation of mean particle size. The method used was based on a relationship obtained by May et al. (1989), which is illustrated in equation 182, and in terms of d_{50} in equation 183.

$$V_t = 0.61\sqrt{g(s-1)R}\left(\frac{d_{50}}{R}\right)^{0.23} \qquad ...182$$

$$d_{50} = \left(V_t \Big/ 0.61\sqrt{g(s-1)}R^{0.27}\right)^{4.34} \qquad ...183$$

This relationship was obtained in rough and smooth pipe studies at the limit of deposition. It was selected for use in this study as each of the parameters were easily measured accurately. The principal alternative to this relationship was that obtained by May (1994) which is illustrated in equation 184. This equation was not used, as when re-arranged in terms of d_{50} (equation 185), the unacceptably large exponent produced highly variable results.

$$V_t = 0.125\sqrt{g(s-1)d_{50}}\left(\frac{y_o}{d_{50}}\right)^{0.47} \qquad ...184$$

$$d_{50} = \left(V_t \Big/ 0.125\sqrt{g(s-1)}y_o^{0.47}\right)^{33.333} \qquad ...185$$

In each case the average flow velocity was used for the threshold velocity (V_t).

Although this method may not be ideal, it does produce results in the appropriate range. In using this method it was anticipated that each of the relationships tested would respond to relative differences in d_{50}, rather than absolute changes.

2. Material Bulk Density

As with the models obtained in experiments investigating sediment transport over deposited beds, all the predictive relationships available for transport at the limit of deposition use a submerged specific gravity parameter *(s-1)* to some extent. However in the laboratory, where the specific gravity of the material used is relatively high, this may be acceptable, but in the field this causes some problems due to the much lower densities under consideration (average ≅1000 - 1108 kg/m^3 for Study 3). This is caused by differences in the bulk density of the material being greatly exaggerated, more so than that of the sediments used in the laboratory, when the submerged specific gravity is determined. Additionally, the bulk density observed in the field is well outside the range used in the laboratory. To overcome this problem caused by the submerged specific gravity term, 3 approaches were investigated;

- Substitute *(s-1)* with ρ_b/ρ_w.
- Substitute *(s-1)* with ρ_d/ρ_w..
- Substitute *(s-1)* with *(2.65-1)*.

Where ρ_b & ρ_d are the bulk density and dry density of the sampled sediment respectively and, ρ_w is the density of water (1000kg/m^3).

7.4.1.1 Laboratory Based Models - Results

As with the models tested on the Study Site 2 data, none of the models used at Study Site 3 produced results in the same range as the field observations. This situation was improved, slightly, when the candidate relationships were modified by application of a coefficient to the results obtained. Tables 67, 68, 69, and 70 give more details of the results of the evaluation exercise. The performance of each model tested is expressed as the number of the 21 DWF data sets for which predictions were obtained within -50% to +100% of the measured transport concentration.

TABLE 67 : EVALUATION OF THE RELATIONSHIP PROPOSED BY Nalluri & Ab. Ghani (1993) - STUDY SITE 3

	ρ_b/ρ_w as $(s-1)$	ρ_d/ρ_w as $(s-1)$	(2.65-1) as $(s-1)$
Performance (No. /21)	10	5	9
Coefficient	160.0	4.411×10^{-3}	28.092
Model Accuracy : $\left(\dfrac{\text{Calculated Transport Rate}}{\text{Measured Transport Rate}}\right)\times 100\%$			
Low (%)	0.810	4.282	0.771
High (%)	746.9	426.9	737.9
STD (%)	161.1	119.7	161.0

TABLE 68 : EVALUATION OF Ab. Ghani (1993) - STUDY SITE 3

	ρ_b/ρ_w as $(s-1)$	ρ_d/ρ_w as $(s-1)$	(2.65-1) as $(s-1)$
Performance (No. /21)	9	5	10
Coefficient	41.59	5.058×10^{-3}	249.5
Model Accuracy : $\left(\dfrac{\text{Calculated Transport Rate}}{\text{Measured Transport Rate}}\right)\times 100\%$			
Low (%)	0.687	4.058	0.723
High (%)	753.8	430.9	763.5
STD (%)	164.5	121.1	164.7

TABLE 69 : EVALUATION OF Nalluri, Ab. Ghani & El-Zaemey (1994) - STUDY SITE 3

	ρ_b/ρ_w as $(s-1)$	ρ_d/ρ_w as $(s-1)$	(2.65-1) as $(s-1)$
Performance (No. /21)	9	4	11
Coefficient	647.2	2.86×10^{-2}	4607.7
Model Accuracy : $\left(\dfrac{\text{Calculated Transport Rate}}{\text{Measured Transport Rate}}\right)\times 100\%$			
Low (%)	0.957	4.995	0.907
High (%)	622.7	303.0	614.7
STD (%)	136.0	109.4	136.6

TABLE 70 : EVALUATION OF May (1994) - STUDY SITE 3

	ρ_b/ρ_w as $(s-1)$	ρ_d/ρ_w as $(s-1)$	(2.65-1) as $(s-1)$
Performance (No. /21)	1	4	3
Coefficient	2106.1	8.79×10^{-3}	1697.4
Model Accuracy : $\left(\dfrac{\text{Calculated Transport Rate}}{\text{Measured Transport Rate}}\right)\times 100\%$			
Low (%)	0.000	5.474	0.001
High (%)	851.5	297.4	766.0
STD (%)	215.9	105.5	183.8

The tables illustrate how inadequately each of the relationships tested performed on the field data, although the performance is increased considerably when coefficients are applied to the original models. The results also suggest that when the submerged specific gravity parameter is replaced with ρ_b/ρ_w.or (*2.65-1*) the relationships perform better than if ρ_d/ρ_w had been used. This may be due to these parameters effectively being constants due to the lack of variation in the bulk density of the samples obtained (average = 1002.6 kg/m^3 and a standard deviation of 27.5kg/m^3) which may represent well the lack of variation of the specific gravity of the material used as a surrogate sediment in laboratory studies (e.g. for May (1994) out of a total of 332 tests the particle density only varied from 2530 - 2650 kg/m^3). Further analysing the results, it can be seen that the evaluation of the laboratory models for transport at the limit of deposition are almost identical, given the nature of the data used, for the trial undertaken using ρ_b/ρ_w.and (*2.65-1*) in place of the submerged specific gravity parameter, this again indicates that because of the lack of variation in the densities of sediments used in the laboratory studies the specific gravity parameter is essentially a constant. The dry density term, however, does vary a great deal with a average range of 26.3 - 122.5kg/m^3 and a standard deviation of 23.2 kg/m^3, and trials using this substitution perform consistently worse than those using ρ_b/ρ_w.or (*2.65-1*) in place of the submerged specific gravity parameter.

The results of the evaluation were further analysed in an attempt to find the source of the large discrepancies produced. The analysis performed indicated that there was a direct correlation with the assumed particle size, $\hat{d}_{50}$, and the level of discrepancy associated with each transport model. The correlation obtained for each of the relationships is illustrated in Figure 61a, b, c, and d. Table 71 gives details of the best fit line obtained for each of the sets of results, where the line fits the general form illustrated in equation 186 for the relationships obtained at the University of Newcastle-Upon-Tyne (Nalluri & Ab. Ghani, 1993, Ab. Ghani, 1993 and Nalluri et al., 1994). Whereas, the for the relationship obtained by May (1994) the results were in the form illustrated in equation 187 ;

$$\left(\frac{\text{Calculated Transport Rate}}{\text{Measured Transport Rate}}\right) = A\hat{d}_{50}^{B} \qquad ...186$$

$$\left(\frac{\text{Calculated Transport Rate}}{\text{Measured Transport Rate}}\right) = Ae^{B\hat{d}_{50}} \qquad ...187$$

Where *A* and *B* are constants.

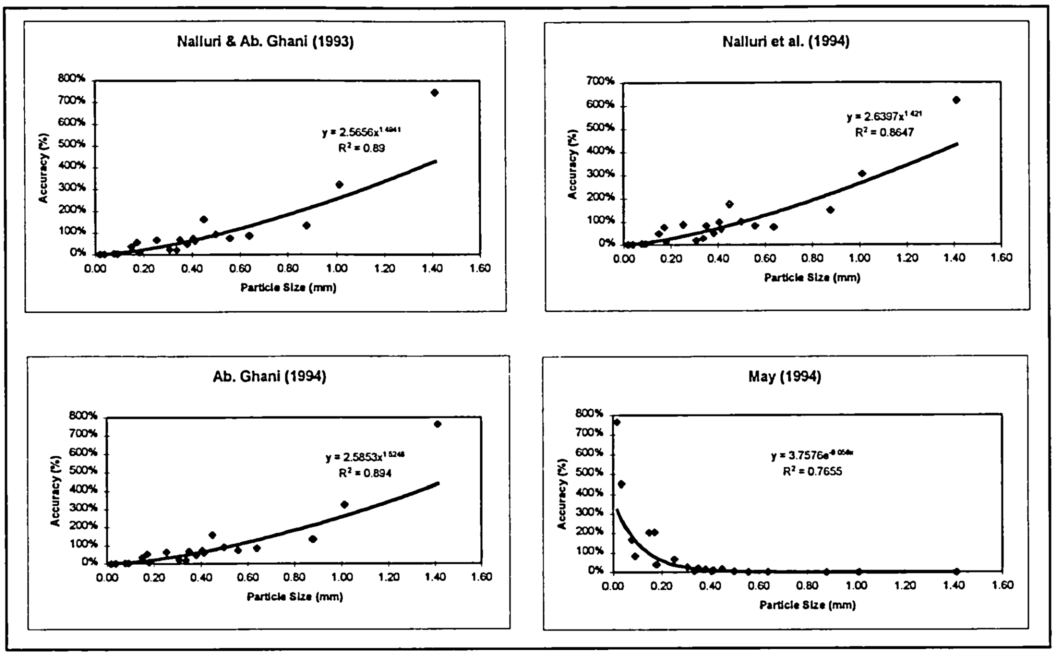

Figure 61 a, b, c, & d : $\hat{d}_{50}$ correlation with the level of error associated with each transport model.

TABLE 71 : CORRELATION OF $\hat{d}_{50}$ WITH THE LEVEL OF ERROR ASSOCIATED WITH EACH TRANSPORT MODEL.

	A	B	r^2
Nalluri & Ab. Ghani(1993)	2.5656	1.4941	0.90
Ab. Ghani (1993)	2.5853	1.5248	0.89
Nalluri et al. (1994)	2.6397	1.4210	0.86
May (1994)	3.7576	9.056	0.77

From these results it can be seen that the substitution of $\hat{d}_{50}$ for d_{50} produced good results only in the mid-range of particle sizes for each of the relationships tested.

The results presented in this section have shown that a laboratory based model could not be utilised to predict the sediment transport concentration at the bed using the data collected. This could be due to a number of factors:

- The range of particle characteristic encountered at the study sites were not represented in the laboratory studies.

- The models cannot represent factors such as inputs to the system, temporal changes in particle characteristics and upstream sediment characteristics.

- Laboratory based models require the accurate estimation of parameters which proved difficult to measure in the field, the most important of which was the particle size characteristics.

- Laboratory based models, in general give results which relate to the transport capacity of the flow, whereas sewers, in general, do not operate at this level of transport. This is because much of the laboratory based models have been concerned with preventing the primarily inorganic particles (grits and gravels) from forming sediment deposits.

7.4.2 Independent Model Development

7.4.2.1 Introduction

The next stage in the data analysis was to attempt to form an independent predictive model which could be used to obtain an accurate estimation of the mass of solids in transport at the invert of the test section. The evaluation of the laboratory based models for transport at the limit of deposition and analysis of the results, indicated that, possibly, these models do not represent accurately some factors relating to sediment transport in a real sewer. Based on this observation, an exercise was undertaken to evaluate which factors affect the transport of material at the bed, based on site observations at each of the 3 field sites used in this study and fieldwork reported by other researchers (Lin at al., 1993a & b and Bertrand-Krajewski, et al., 1995). The factors which were considered to be important are discussed below;

- Ambient Hydraulic Conditions

  These factors control the nature of the material in transport, if present. Ambient hydraulic conditions are represented in all the laboratory based models investigated, and are commonly in the form of a modified form of the Froude number, F_r.

- Inputs to the System

  In sewerage systems, in general, inputs vary considerably throughout an average DWF day. Typically, liquid and solids inputs to the system are well correlated (Crabtree et al., 1993) with the main peak in input being at the start of the day, (07:00 - 08:00am) with additional peaks around mid-day and early evening. Conversely inputs to the system reduce considerably during the early morning (00:00 - 06:00). This situation may be exacerbated in the days immediately following a large storm when infiltration of runoff, of typically low solids content, into the sewerage system can make up a considerable proportion of the flows and consequently further dilutes the solids and other pollutants in the flow.

Clearly, solid inputs to the system are important when trying to predict the transport of solids at the bed. However, predictive relationships which have been obtained as part of laboratory studies assume a constant, and infinite, mass of sediment available for transport. In addition, the sediment transport concentration is often at, or near, the transport capacity of the flow.

- Upstream Sediment Bed Characteristics
  Clearly the lack, or presence, of a sediment bed upstream of a given point in a sewer system will affect, to some extent, the rate of sediment transport. A storm, depending on the rainfall characteristics, can cause a significant amount of erosion, or deposition, of sediments in any given length of sewer. Where a large amount of deposition has occurred the deposit may be eroded during DWF conditions, if the flow has sufficient energy, thus increasing the mass of sediment in transport. Conversely if a sediment bed has been eroded, the material travelling at the bed has been hypothesised (Lin & Le Guennec, 1995) to be a source of material for deposition, this situation can reduce the amount of material in transport. Although the characteristics of the previous storm may affect the transport at the bed, the influence of any given rainfall event will diminish with time.

- Transported Particle Characteristics
  The characteristics of an individual sediment particle are perhaps amongst the most important factors which are considered in theoretical transport studies. However, given the diverse nature of the material sampled in sewers it is, generally, difficult to characterise individual particles.

This process in selecting influencing factors is similar to that employed in laboratory studies. Ab Ghani (1993) highlighted five factors which were deemed to be important in the Newcastle based laboratory study:

- Mobility parameters
- Transport parameters
- Sediment characteristics
- Conveyance shape
- Flow resistance

Examples of each of these characteristics are given in Table 72.

TABLE 72 : CHARACTERISTIC PARAMETERS TESTED BY Ab Ghani (1993) FOR SEDIMENT TRANSPORT IN A LABORATORY

Parameter Type	**Example of Group**
Mobility parameters	$F_{rm} = \dfrac{V}{\sqrt{gd_{50}(s-1)}}$
Transport parameters	$\Phi = \dfrac{C_v VR}{\sqrt{g(s-1)d_{50}^3}}$
Sediment characteristics	D_{gr} or d_{50}/D
Conveyance shape	R/d_{50} or y_o/D
Flow resistance	λ_b or $(k_{sb} - k_o)/D$

Although the use of these groups of parameters by Ab Ghani (1993) was successful, the same groups are not necessarily as important in this study. This being due to the Newcastle based researcher being concerned with sediment transport concentrations at the capacity of the flow in a study which could not consider factors such as inputs to the system or upstream sediment characteristics, or variations in flow and sediment supply rates.

7.4.2.2 Methodology

The generation of a predictive relationship was based on the multiple, and linear, regression of dimensionless groups of relevant parameters. The groups were established using dimensional analysis of parameters selected based on laboratory and field observations. Once the dimensionless groups were formed they where divided into four groups, corresponding to the influencing factors outlined in the previous section, i.e.

1. Ambient Hydraulic Conditions
2. Inputs to the System
3. Upstream Sediment Bed Characteristics
4. Transported Particle Characteristics

A full list of the dimensionless parameter groups tested is given in Appendix F, along with the factors they were proposed as representing. In attempting to obtain a relationship via multiple regression, dimensionless groups were selected which represented each of the influencing factors, and then any correlation between the candidate groups and the near bed solids transport concentration was tested. The data were considered in four forms:

1. x
2. $x^{1/2}$
3. x^2
4. $\log_{10}x$

The regression analysis could then produce tentative relationships in the form illustrated in equations 188 and 189;

$$C_v = \beta_0 + \beta_1 x_1 + \beta_2 x_2 .... \beta_k x_k \qquad ...188$$

$$C_v = \beta_0 x_1^{\beta_1} x_2^{\beta_2} ... x_k^{\beta_k} \qquad ...189$$

Where β_0, β_1, etc. are constant coefficients and x_1, x_2, etc. are dimensionless groups. Because of the availability of data, *k* was limited to six to limit the degrees of freedom and also to ensure any relationship obtained was not too cumbersome to apply.

7.4.2.3 Results

In undertaking the analysis only 19 of the 21 data sets were used, the remaining 2 (data sets 1 & 2) were reserved to validate any resultant candidate relationships. The regression analysis produced 6 tentative relationships which performed within the initial target range of -50% to +100% of the measured transport concentration. The performance of each of the relationships is illustrated in figures 62, 63, 64, 65, 66 and 67 and the respective relationships are detailed in equations 190, 191, 192, 193, 194, and 195, and in Table 73.

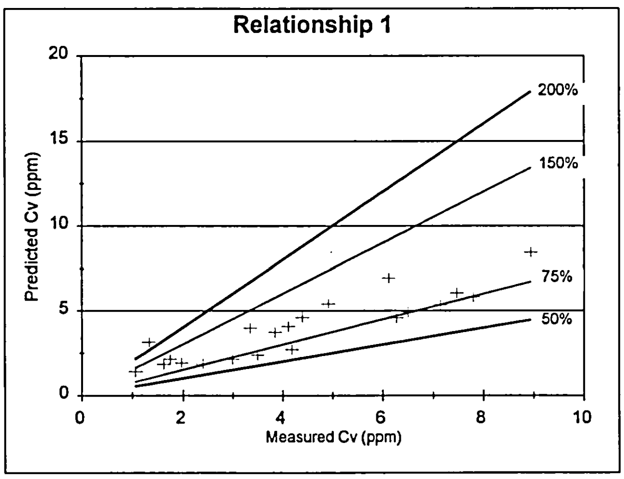

Figure 62 : Relationship 1 Performance

Relationship 1

$$C_v = a_1 + b_1\left(\frac{I_r TSSS}{D_r}\right) + c_1\left(\frac{y}{y_{max}}\right) + d_1\left(\frac{\tau_o}{\tau_b}\right) + e_1\left(\frac{\rho_d}{\rho_w}\right) \qquad ...190$$

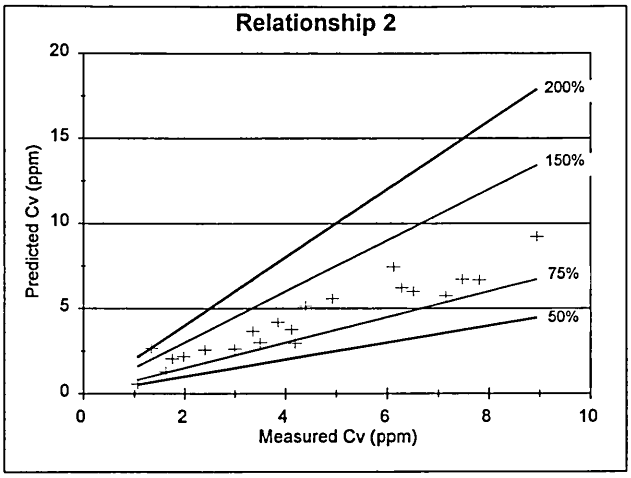

Figure 63 : Relationship 2 Performance

Relationship 2

$$C_v = a_2 + b_2\left(\frac{\rho_d}{\rho_w}\right)^2 + c_2\left(\frac{y}{y_{max}}\right)^2 + d_2\left(\frac{I_r TSSS}{D_r}\right)^2 + e_2\left(\frac{\tau_o}{\tau_b}\right)^2 + f_2\left(\frac{Q}{Q_{max}}\right)^2 + g_2\left(\frac{\hat{d}}{R}\right)^2 \qquad ...191$$

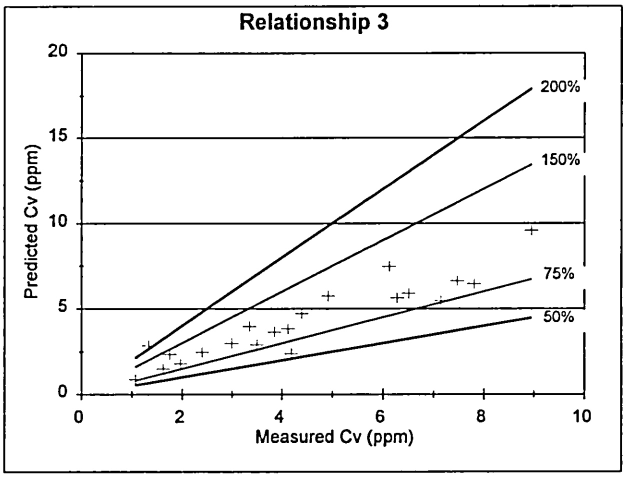

Figure 64 : Relationship 3 Performance

Relationship 3

$$C_v = a_3 + b_3\left(\frac{\rho_d}{\rho_w}\right)^2 + c_3\left(\frac{V^2}{gsy}\right)^2 + d_3\left(\frac{y}{y_{max}}\right)^2 + e_3\left(\frac{I_r TSSS}{D_r}\right) + f_3\left(\frac{Q}{Q_{max}}\right)^2 + g_3\sqrt{\left(\frac{R}{\hat{d}}\right)} \qquad ...192$$

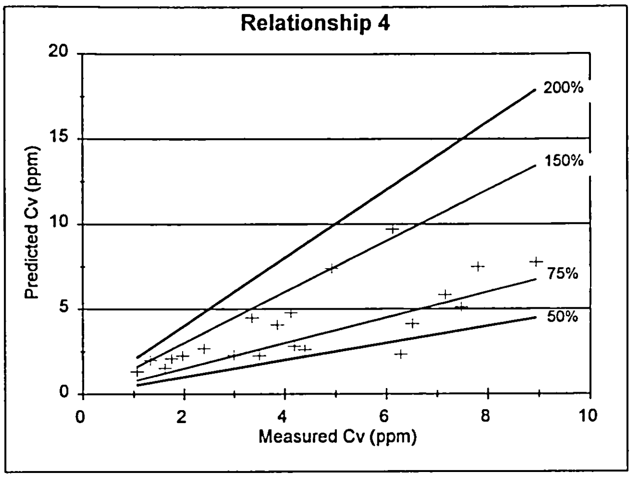

Figure 65 : Relationship 4 Performance

Relationship 4

$$C_v = a_4\left(\frac{\rho_d}{\rho_w}\right)^{b_4}\left(\frac{\tau_o}{\tau_b}\right)^{c_4}\left(\frac{D^2}{A}\right)^{d_4}\left(\frac{I_r TSSS}{D_r}\right)^{e_4} \qquad ...193$$

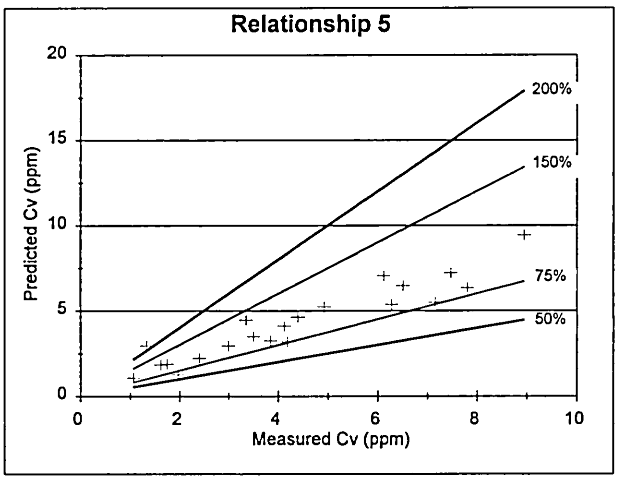

Figure 66 : Relationship 5 Performance

Relationship 5

$$C_v = a_5 + b_5\left(\frac{\rho_d}{\rho_w}\right) + c_5\left(\frac{v}{v_{max}}\right) + d_5\left(\frac{y}{y_{max}}\right) + e_5\left(\frac{Q}{Q_{max}}\right) + f_5\left(\frac{I_r TSSS}{D_r}\right) + g_5\left(\frac{\tau_o}{\tau_b}\right) \qquad ...194$$

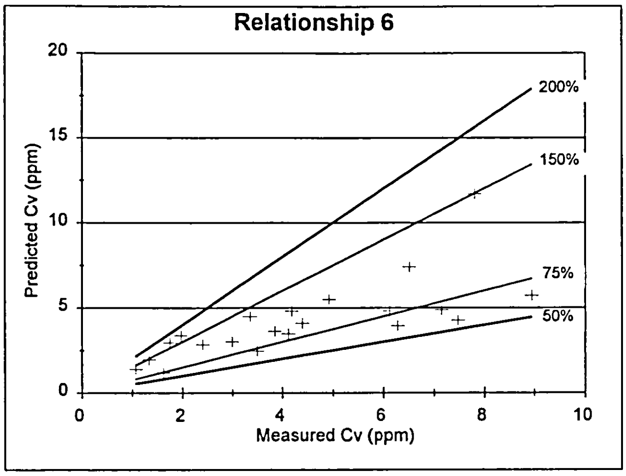

Figure 67 : Relationship 6 Performance

Relationship 6

$$C_v = a_6 \lambda^{b_6} \left(\frac{d_{50}}{R}\right)^{c_6} \left(1 - \frac{V_t}{v}\right)^{d_6} \quad \ldots 195$$

TABLE 73 : CANDIDATE RELATIONSHIP DETAILS

	a	*b*	*c*	*d*	*e*	*f*	*g*	r^2 (%)
Relationship 1	-105.73	2.55×10^{-3}	0.2023	47.808	120.45	NA	NA	75.7
Relationship 2	-68.89	865.1	4.59×10^{-3}	3.59×10^{-6}	11.444	-9.78×10^{-4}	-3535	86.0
Relationship 3	-29.74	860.9	-10866	3.66×10^{-3}	3.30×10^{-3}	-7.97×10^{-4}	7.08×10^{-2}	82.5
Relationship 4	6.65×10^{-04}	2.185	34.87	-16.75	0.209	NA	NA	66.5
Relationship 5	-226.9	155.7	1.230	1.175	-1.311	4.51×10^{-3}	65.69	84.5
Relationship 6	$10^{-113.67}$	-57.82	5.694	66.79	NA	NA	NA	66.3

TABLE 74 : STUDY SITES 2 & 3 DATA ENVELOPES

		C_v (ppm)	I_r (mm/h)	D_r (mm)	*TSSS* (h)	*ADWP* (h)	y_d/y_{max} (%)	τ_o (N/m²)	τ_b (N/m²)	ρ_d (kg/m³)
Study Site 3	Min	1.1	1.2	0.4	5.6	4.3	85	0.033	0.018	26.3
	Max	9.0	24.0	11.4	179.4	178.1	100	0.236	0.144	122.5
	AVG	4.4	5.3	2.7	71.9	73.3	95.2	0.124	0.074	78.6
	S.D.	2.9	6.3	3.3	49.8	51.1	4.7	0.050	0.031	8.20
Study Site 2	Min	9.8	2.0	0.5	33.0	32	87.4	0.354	0.217	160.50
	Max	16.0	12.0	6.0	229.6	226.1	99.6	0.632	0.393	266.1
	AVG	13.0	5.2	2.2	122.1	117.4	94.9	0.498	0.308	196.5
	S.D.	2.6	3.7	2.0	63.4	62.6	4.2	0.097	0.061	40.23

The next stage in the verification of each of the six candidate relationships was to apply them to data collected at other points in the network. In doing this it was anticipated that a relationship would be found which would have the widest possible applicability. The data used to further validate the candidate relationships were those collected as part of Study Site 2. Although Study Sites 2 and 3 are in the same sewer they are a considerable distance apart (~650m), and there are substantial inputs to the sewer between the 2 sites (see section 5.1 "Catchment Details"). Additionally, there are considerable differences in the sampled material characteristics and ambient hydraulic conditions, as illustrated in Table 74.

The relationships were then applied to the data collected at Study Site 2 The results of the evaluation can be seen in Table 75.

TABLE 75 : VERIFICATION USING STUDY SITE 2 DATA

		1	2	3	4	5
Study 2	Measured Cv	13.03	10.35	16.04	9.78	15.64
Relationship 1	Predicted Cv	11.80	17.56	25.70	12.41	12.35
	Accuracy	90.57%	169.56%	160.23%	126.94%	78.99%
Relationship 2	Predicted Cv	14.90	32.66	54.60	3.00	-5.38
	Accuracy	114.32%	315.42%	340.34%	30.64%	-34.42%
Relationship 3	Predicted Cv	3.38	25.48	43.38	-13.23	-19.77
	Accuracy	25.89%	246.12%	270.42%	-135.32%	-126.45%
Relationship 4	Predicted Cv	3.960×10^{-16}	2.610×10^{-16}	1.042×10^{-15}	9.140×10^{-17}	1.268×10^{-16}
	Accuracy	0.00%	0.00%	0.00%	0.00%	0.00%
Relationship 5	Predicted Cv	18.86	29.84	31.28	20.50	17.19
	Accuracy	144.73%	288.17%	194.99%	209.69%	109.91%
Relationship 6	Predicted Cv	5.37×10^{-10}	1.76×10^{-11}	1.81×10^{-10}	8.76×10^{-11}	3.55×10^{-10}
	Accuracy	0.00%	0.00%	0.00%	0.00%	0.00%

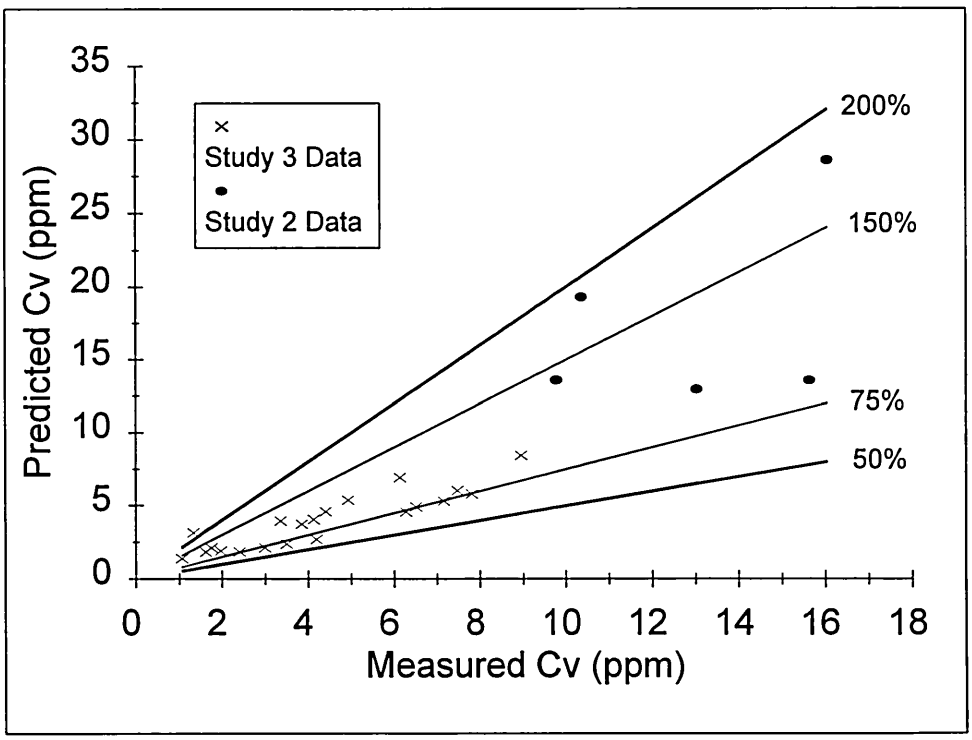

Figure 68 : Performance of Relationship 1 on Study 2 & 3 Data

As the table indicates, only relationship 1 produced results in the range sought, with relationships 4 and 6 performing the poorest. The performance of Relationship 1 (equation 196) on the Study Site 2 and 3 data is illustrated in Figure 68, where C_V is expressed in parts per million (ppm). The data illustrated in figure are also given in Table 76.

$$C_v = -105.73 + 2.55 \times 10^{-3}\left(\frac{I_r TSSS}{D_r}\right) + 0.2023\left(\frac{y_o}{y_{max}}\right) + 47.808\left(\frac{\tau_o}{\tau_b}\right) + 120.45\left(\frac{\rho_d}{\rho_w}\right) \qquad ...196$$

TABLE 76 : PERFORMANCE OF RELATIONSHIP 1 ON STUDY 2 & 3 DATA

Data Set	1#	2#	3	4	5	6	7
Measured C_V (ppm)	6.3	4.2	3.4	6.1	7.2	7.8	4.9
Predicted C_V (ppm)	4.6	2.7	4.0	6.9	5.3	5.8	5.4
Accuracy	73.1%	64.9%	118.9%	113.4%	74.7%	74.7%	109.9%

Data Set	8	9	10	11	12	13	14
Measured C_V (ppm)	4.4	4.1	2.0	1.6	3.9	3.0	3.5
Predicted C_V (ppm)	4.6	4.1	1.9	1.8	3.7	2.1	2.4
Accuracy	105.1%	99.1%	97.4%	113.3%	97.3%	71.3%	68.2%

Data Set	15	16	17	18	19	20	21
Measured C_V (ppm)	1.8	7.5	9.0	1.1	1.3	6.5	2.4
Predicted C_V (ppm)	2.1	6.1	8.5	1.4	3.1	4.9	1.9
Accuracy	122.3%	80.9%	94.4%	131.0%	236.0%	75.9%	78.0%

Data Set	SS2 - 1#	SS2 - 2#	SS2 - 3#	SS2 - 4#	SS2 - 5#
Measured C_V (ppm)	13.0	10.4	16.0	9.8	15.6
Predicted C_V (ppm)	11.8	17.6	25.7	12.41	12.53
Accuracy	90.6%	169.6%	160.2%	126.9%	79.0%

As this relationship performs remarkably well on the data collected at Study Site 3, the validation data obtained at Study Site 3 and that amassed at Study Site 2, and better than the five other relationships, it is proposed as being the best methodology for predicting the transport concentration of sediment at the bed at the sites considered. The proposed relationship models the transport of sediment at the bed as being composed of seven distinct parameters, which represent four factors which are described below;

(a) $2.55 \times 10^{-3} \times \left(\frac{I_r TSSS}{D_r}\right)$

Where I_r, D_r and TSSS are the Maximum rainfall intensity, Total depth of rainfall and Time since the start of the previous storm respectively. The parameters relate to the details of the last storm of a total depth in excess of 0.4mm, as this was considered to be the smallest rainfall event which would generate an increase in flow conditions in the sewer considered, and hence possibly cause some erosion of the deposited sediment bed upstream of the Study Site.

Validation data sets, SS2 - Study Site 2 validation data set

It is hypothesised that this group of parameters, to some extent, represents the characteristics of the upstream sediment bed and the affect the previous rainfall event has had on it. As time elapses since the last storm (TSSS), this component has an increasing influence on the mass transported. Other researchers (Stotz & Krauth, 1984, Coghlan, 1995 and Coghlan et al., 1995) have identified TSSS and similar parameters (ADWP - antecedent dry weather period, effectively time since the end of the last storm) as being important in the prediction of solids in transport during storm conditions, with varying degrees of success. Due to the nature of the storms experienced pervious to each of the data collection exercises it proved problematic to use TSSS and ADWP together as the two parameters were well correlated, furthermore TSSS provided the best results, statistically, in the regression analysis. This may be due to TSSS representing erosion of the upstream sediments at the onset of the rainfall event. Additionally, Gupta & Saul (1995), in a study of five catchments, developed a first flush model which relates the *total pollutant load* to: storm duration, maximum rainfall intensity and antecedent dry period. The *peak concentration* was found to be related to a rainfall ratio and antecedent dry period (the work presented by Gupta and Saul (1995) is discussed in section 2.6 "First Flush"). Whilst these catchment studies are more 'global' than the detailed work presented here, they do provide support for the use of parameters, albeit that this equation relates to the transport during dry weather of material available for incorporation in a foul flush when it rains.

If, as hypothesised, this relationship does represent upstream sediment characteristics, it is possible that the relationship may not be applicable where there is no upstream deposited sediment bed.

(b) $0.2023 \times \left(\dfrac{y_o}{y_{max}} \right)$

Where y_0 is the depth at the time of day the samples were obtained, as a proportion (expressed as a percentage) of the average DWF maximum depth, y_{max}. The same average DWF hydrograph was used for all the data sets, as it was the time in the flow pattern which was important not the absolute flow conditions. Solid inputs to the system, typically, vary with liquid inputs to the system. Based on this observation, depth variations throughout an average DWF day were used to represent flow and hence solids input to the sewerage system.

(c) $48.808 \times \left(\frac{\tau_o}{\tau_b}\right)$

Where τ_o and τ_b are the shear stress calculated using the average flow velocity, and the flow velocity 50mm# above the bed respectively. This dimensionless group was used to represent ambient hydraulic conditions in the test rig. It is hypothesised that this parameter may represent how, at higher bed shear levels, material moving along the bed is entrained to higher in the flow column and transported there.

(d) $120.45 \times \left(\frac{\rho_d}{\rho_w}\right)$

Where ρ_d and ρ_w are the dry density of the sediment sample and the density of water respectively. This parameter group was used in the regression analysis and showed that it best represented the characteristics of the material moving at the bed. However, it is evident that this parameter must be reliant on other factors to some extent, i.e.; ambient flow conditions and inputs to the system.

7.4.2.4 Model Sensitivity

The next stage in the model development was to assess the sensitivity of the relationship to changes in each of the dimensionless parameter groups. The results of the sensitivity analysis are shown in Tables 77, 78, 79 and 80.

TABLE 77 : SENSITIVITY ANALYSIS FOR $\left(I_r TSSS / D_r\right)$

Increase in Dimensionless Group (%)	1	2	5	10	15	30	50	100
Increase in Predicted C_v (%)	0.2	0.4	1.0	2.0	3.1	6.1	10.2	20.5

TABLE 78 : SENSITIVITY ANALYSIS FOR $\left(y_o / y_{max}\right)$

Increase in Dimensionless Group (%)	1	2	5	10	15	30	50	100
Increase in Predicted C_v (%)	6.2	12.4	31.1	62.2	93.3	186	311	622

TABLE 79 : SENSITIVITY ANALYSIS FOR $\left(\tau_o / \tau_b\right)$

Increase in Dimensionless Group (%)	1	2	5	10	15	30	50	100
Increase in Predicted C_v (%)	26.4	52.9	132	264	397	794	1322	2644

A depth of 50mm was used as this was as close as possible a velocity reading could be obtained using the propeller meter employed.

TABLE 80 : SENSITIVITY ANALYSIS FOR $\left(\rho_d/\rho_w\right)$

Increase in Dimensionless Group (%)	1	2	5	10	15	30	50	100
Increase in Predicted C_V (%)	2.7	5.5	13.7	27.3	41.0	81.9	136	237

The results of the sensitivity analysis indicate that the parameter $\left(\tau_o/\tau_b\right)$, produced the greatest sensitivity to change. This may be due to the small range over which the parameter varied (1.63 to 1.83) and the group has the highest coefficient which further emphasises any variation. Whilst that group $\left(I_r TSSS/D_r\right)$, has the least sensitivity and the highest degree of variation (7.5 - 1114.5) and the smallest coefficient. The ranges obtained for each of the dimensionless parameter groups in the proposed relationship are given in Table 81.

TABLE 81 : RANGE OF VALUES FOR EACH DIMENSIONLESS GROUP - STUDY SITE 3 DATA

Parameter	HIGH	AVG	LOW	STD
$\left(I_r TSSS/D_r\right)$	1114.5	260.2	7.5	304.7
$\left(y_o/y_{max}\right)$	100.0%	95.2%	85.0%	4.7%
$\left(\tau_o/\tau_b\right)$	1.8003	1.6802	1.6343	0.0391
$\left(\rho_d/\rho_w\right)$	0.1225	0.0783	0.0263	0.0235

TABLE 82 : RANGE OF VALUES FOR EACH DIMENSIONLESS GROUP - STUDY SITE 2 DATA

Parameter	HIGH	AVG	LOW
$\left(I_r TSSS/D_r\right)$	389.5	296.2	205.2
$\left(y_o/y_{max}\right)$	99.6%	94.9%	87.4%
$\left(\tau_o/\tau_b\right)$	1.607	1.616	1.629
$\left(\rho_d/\rho_w\right)$	0.266	0.197	0.161

The Study Site 2 data were successfully used to verify the model, as discussed in the previous section. Table 82 gives the range of values obtained for each of the dimensionless groups in the proposed relationship. It can be seen that each of the dimensionless groups were within the range of data collected at Study Site 3, other than that for the group (ρ_d/ρ_w) which was higher.

Based on the sensitivity analysis, it is recommended that the application of the model be limited to data within the range of values obtained at Study Site 3, although where the relationship is applied outside this range the results may be satisfactory.

However, in applying this relationship some caution should be placed on the results as the model may only be site specific. This is unavoidable given the limited financial and time constraints of this project. The relationship is patently more applicable where the sewer, catchment and climate are as close as possible to those experienced in the Dundee. The work reviewed in chapters 2 and 3 of this report has highlighted the high degree of variation of solids in transport in combined sewer systems, although some of this variation is possibly due to data collection methodologies and analysis techniques employed. These findings further emphasise the site, or catchment, specific nature of the relationship proposed for the prediction of near bed solids transport.

7.4.2.5 Model Application

The aim of this study was to produce a relationship which could generate an accurate prediction of the mass of material in transport near the bed in combined sewers systems, based on easily measurable parameters. In the previous sections the development of the relationship has been discussed, and in this section the application of the relationship will be described.

7.4.2.5.1 Data Requirements

The principal data requirements for the relationship are as follows:

1. Rainfall relating to the previous storm, i.e. depth, intensity, duration and antecedent dry weather period.

2. An 'average' dry weather flow depth profile for the site considered.

3. Ambient velocity conditions for the site considered, at the point in the DWF profile of interest.

4. An estimation of the dry density of the material in transport. This parameter, perhaps is the most difficult to obtain accurately, and is

sensitive to change, i.e. an increase of 10% in the parameter gives a resultant increase of 27.3% in the transport concentration. The model will be substantially easier to apply if the tentative relationship between dry density and ambient velocity conditions, discussed in section 6.3.1.1.3 "Bulk Density", is further developed.

7.4.2.5.2 Application

The application of the relationship is straightforward, and as follows:

1. Determine average shear stress, τ_o, and the bed shear stress, τ_b.
2. Determine y_o/y_{max} from the average DWF depth profile.
3. Determine TSSS, I_r and D_r for the previous storm from the rainfall data.
4. All the calculated and measured parameters are then entered into the relationship and Cv is computed. The transport concentration near the bed, C_v, is estimated in parts per million (ppm) using the relationship, which is equivalent mg/l.
5. For storm events the impact the near bed solids have on the first foul flush may then be estimated using the approach described in section 6.5 "Discussion". The influence material eroded from any deposited bed has on the first flush may be estimated, to some extent, using the work of Wotherspoon (1994).
6. For DWF conditions the suspended solids concentration may then be estimated using the work of other researchers (e.g. Coghlan, 1995) to give a full representation of the total solids in transport (i.e. as near bed solids and in suspension).

An example of the application of this methodology is given in Appendix J.

7.5 Conclusions

In conclusion, the results presented in this chapter may be summarised as follows;

The collection of data to enable a rigorous application of the laboratory based models for sediment transport at the limit of deposition and over a deposited bed proved difficult, for the degree of accuracy required.

Laboratory based models were applied, with some degree of success, to sites with and without sediment deposits to estimate the near bed solids transport concentration, although some modification of the relationships was required. As with the laboratory evaluation of the relationships (Ackers et al., 1994) the models relating to transport over a deposited bed were found to perform best. Although, this result may be due to differences observed in the material in transport at the two sites.

At Study Site 2 modified relationships were obtained which could be used to predict the inorganic mass, and the total mass of material in transport at the bed, although the data used for the model developed are limited quantitatively. The proposed models do, however, highlight the parameters which may be important when considering sediment transport over a deposited bed in a combined. sewer.

Application of the available laboratory based sediment transport models highlights the inability of these relationships to account for site specific factors such as inputs to the system and upstream characteristics. This is principally due to the laboratory based models normally being developed at the transport capacity of the flow for the transport of inorganic grits and gravels.

Based on the data collected at Study Site 3, a novel sediment transport methodology was obtained, which may be used to predict the material in transport near the bed. The groups of parameters in the relationship were selected to represent four distinct factors:

The characteristics of the transported material
Ambient hydraulic conditions
Inputs to the system
Upstream sediment characteristics

The relationship performed well on both the Study Site 3 data, and that collected at Study Site 2. The model development was based on 19 DWF data sets collected at Study Site 2. The model was than validated using 2 DWF data sets from Study Site 3 and 5 DWF data sets from Study Site 2. Overall, the relationship provided results within the range sought (-50% to +100%).

Although the relationship obtained appears to perform well for the data collected as part of Study 3, on the validation data, and the data collected as part of Study 2, it does not address the fundamental phenomena which control particle motion at the bed in combined sewers. Indeed, given the nature of data collection in real sewers it is difficult to see how this problem may be examined without observations affecting the mechanisms involved. The relationship does however give an indication of the factors which influence near bed solids transport in the Dundee interceptor sewer, and further afield, which cannot be represented in the laboratory.

When the relationship is used to predict the near bed solids transport it becomes possible to estimate the impact the material in transport would have on the first flush if it occurred at the point in time considered using the approach outlined in section 6.5 “Discussion”. The application of the relationship was illustrated based on the data collected at the study site and a real storm pollutograph.

Chapter 8 : Conclusions and Recommendations for Further Research

The programme of research presented in this report represents the first concerted study dealing with the movement of solids near the bed in combined sewer systems. For the first time it has been possible to link the rate of transport near the bed in sewers, in a field based study, to influencing factors. This study is not only important due to the results presented here, but also because it highlights the importance of further research investigating this phase of solids transport in sewers.

8.1 Data Collection

A sampling methodology was established which could be used to collect a representative sample of the material moving at the bed in the Dundee combined sewerage system, and further afield (see Chapter 5). The data collected highlighted the unsuitability of small bore samplers for obtaining a representative sample of the solids moving at the bed (see section "6.3.2 Suspended Solids Transport"). This was principally due to the failure of small bore samplers to supply an accurate representation of the larger solids moving at the bed. This was due to the larger particles blocking the sampling hose and effectively acting as a filter.

8.2 Material Characteristics

A distinct variation in the characteristics of the material moving at the bed was observed at different points in the Dundee sewerage system. Considerable differences were observed in particle size, organic content and material density characteristics, based on data collected at three field sites.

Generally, it was observed that at locations in the sewerage network with high velocity hydraulic conditions, the near bed solids could be characterised as being of low organic contents and relatively high specific gravity. Conversely, where ambient hydraulic conditions are relatively low, the material in transport was characterised as being of high organic content and low bulk density (see section 6.3.1.1 "Physical Characteristics"). This observation is principally due to the higher flow velocities having sufficient energy to hold larger inorganic solids (grits) in transport, whist lighter (organic) solids are held in suspension.

Little variation was observed in the bulk density of the material moving at the bed at Study Site 3 (see section 6.3.1.1.3 "Bulk Density"). This being primarily due to the high organic content of the material in transport near the bed of this site, owing to the lower ambient bed shear conditions. The dry density of the near bed solids, however, was seen to vary considerably. A tentative correlation was observed which linked the dry density of the near bed solids to the ambient velocity conditions, although more data are required if this is to be developed.

At each of the study sites established, variations in the characteristics of the material in transport near the bed were noted throughout the DWF pattern (see section 6.3.1.3 "Transport Rates"). These variations were perceived as representing inputs to the system, and, to some extent, ambient hydraulic conditions. The solids in transport are linked to hydraulic conditions, as at the peaks and troughs of the DWF velocity pattern, material will be eroded and deposited respectively, causing the nature of the material in transport to vary continuously. Inputs to the system will influence the nature of the material in transport due to the changing human activities in the catchment during a given time period.

The pollution potential of the material moving at the bed was also investigated. Considerable variation in the COD, BOD_5 and ammonia levels associated with the near bed solids mode of transport were noted. Variations in the pollutant potential were hypothesised as being dependent on inputs to the system. A tentative relationship was obtained which linked the ammonia levels associated with the material in transport near the bed to inputs to the system (see section 6.3.1.3.2 "Pollutant Transport Rates").

Settling velocity tests confirmed that the material moving at the bed had a higher settling velocity than concurrently sampled sewage. This being due to higher densities and particle sizes associated with the material in transport at the bed (see section 6.3.1.1.4 "Settling Velocity").

In Section 2.4 "Sediment Transport" the transport of sediment as "bed-load" in sewers was discussed, and for the purposes of this study the mode of transport was termed *Near Bed Solids* (NBS) transport. This terminology was used as it was idealised as describing the transport of solids near the bed in every sewer. The 'dense undercurrent' terminology proposed by Verbanck (1995), and others like it, was discounted as they assume the solids moving near the bed are transported in a dense suspension, and this was found not to be the case in Dundee. No data were found in this project which suggested this was the case. Indeed, Verbanck (1995) offers only subjective analysis of limited data to support the 'dense undercurrent' terminology. It is the opinion of the author, formed through observations in the field, that the larger (organic) solids (>1mm) in transport near the bed are transported primarily by saltation, or rolling, as discrete particles. These larger solids are surrounded by a suspended solids concentration which may be slightly higher than average for the flow column, but not near the point at which a hindered settling matrix would form. Although these observations are based solely on the data collected and observations made in Dundee, no evidence can be found to show that this is not the case elsewhere. The transport as near bed solids, but not the actual material itself, in sewers may perhaps best be described by the terminology proposed by Einstein (1944) for bed-load transport:

> **"...the transport of sediment particles ...... just above the bed by sliding, rolling and sometimes making jumps of a few particle diameters..."**

8.3 Transport Rates

The rate of solids transport at the bed was compared with other modes of solids transport at each of the study sites. At the trunk sewer site, the near bed solids mode of transport was demonstrated as representing up to 78.2% of the total solids measured in transport. Whilst at the two interceptor sewer sites, the mode of transport represented only 0.74 - 10.1% of the total solids measured in transport (see section 6.3.1.3 "Transport Rates"). The transport concentration of material at the bed during DWF conditions was found never to be in the ranges used in the laboratory based studies, which are predominately at the transport capacity of the flow. Whilst this may primarily be due to the limited availability of material for transport, it is possible sediment concentrations observed near the bed in laboratory studies may never occur in sewers such as the Dundee interceptor (low velocities and slack invert gradients). This being due to the solids in transport near the bed in the field being of lower bulk density, and at higher transport concentrations would effectively 'clog' the effective transport width of the conduit substantially before the (dry) mass in transport is equivalent to that utilised in laboratory based studies is reached. Hence the transport capacity of a conduit in the field, where organic sediments are considered, may actually be lower than that observed in laboratory studies.

The flux of chemical and biochemical pollutants associated with the solids in transport at the bed was also investigated. It was found that although the near bed solids mode of transport represented only an average of 2.54% of the solids measured in transport, the pollution potential of the material was up to 43.4% and 54.4% of the total COD and BOD_5 measured in transport respectively (see section 6.3.1.3.2 "Pollutant Transport Rates"). In addition to the biochemical pollution impact, the aesthetic pollution caused by the discharge into the environment (via CSO structures during storms) of the type of material observed in transport as near bed solids in this study is considerable

Based on the sediment transport concentrations near the bed, and the flux of the associated pollutants, a link was hypothesised between this mode of transport and the first foul flush. The hypothesis (section 6.5 "Discussion") is based on existing laboratory studies and computer simulations of a simple single pipe case. The proposed model for near bed solids contribution to the first flush was developed by considering a theoretical sewer length, with no deposited sediment, or lateral inputs. The storm wave was idealised as progressing along a length of sewer, segregated into three discrete sections, each with an individual ambient velocity. The front of the storm wave was then represented as consisting of overtaken base flow (DWF travelling faster than normal due to the surge wave). In the overtaken region, the increased velocity conditions result in the near bed solids being entrained into suspension, increasing the mean suspended sediment and pollutant concentration. Although this approach, in its current state, may be oversimplifying the phenomena, it does have considerable potential for further development. Additionally, the approach offers a valuable novel link between the near bed solids mode of transport and first foul flush in combined sewer systems.

8.4 Model Development

Existing laboratory based models for transport at the limit of deposition and over deposited beds were evaluated. A modified relationship was proposed for total solids transport over a deposited bed, based on data collected at Study Site 2 (section 7.3 "Study Site 2 : Interceptor Sewer, Head of System"). The relationship represents solids transport as a function of: hydraulic conditions, conduit characteristics and sediment properties

Application of models for transport at the limit of deposition proved problematic, there were two reasons for this. Firstly, it was found that the material used in laboratory studies as a surrogate for sewer sediment is not entirely representative of the material observed in transport at the Dundee system sites. Secondly, accurate determination of the parameters required for the application of the laboratory based models proved difficult (section 7.3 "Study Site 3 : Downstream Interceptor Site"). The application of the existing sediment transport models to large diameter sewers must be questioned. Especially where, as is the case in the Dundee interceptor sewer; the deposited sediment bed characteristics vary considerably over short lengths of sewer (d_{50} - 0.09mm to 2.0mm over 600m); the invert gradient is slack and there are numerable side connections. This bears very little relation to the narrow range over which data are collected in laboratory studies, where the sediment in transport is inorganic.

As none of the existing relationships for transport at the limit of deposition performed accurately using the data collected, an attempt was made to formulate an independent near bed solids transport methodology (as described 7.4.2 "Independent Model Development"). A relationship was obtained, via multiple regression of related dimensionless parameter groups, which related transport near the bed to four influencing factors. The factors which were hypothesised as influencing near bed solids transport were: transported material characteristics, ambient hydraulic conditions, upstream conditions and inputs to the system. The application of the methodology was demonstrated, and was shown to be straight forward.

The relationship obtained (see section 7.4.2 "Independent Model Development") provided results, within a reasonable degree of accuracy for data obtained at two points in the Dundee interceptor sewer. However, the relationship is still to be applied outside Dundee. It is anticipated that the application of the methodology outside Dundee may, however, be problematic due to its site specific nature. The methodology does, however, highlight the factors which were found to influence near bed solids transport in combined sewers.

8.5 Summary

In summary the following principal conclusions may be drawn:

- Significant progress has been made in characterising the nature of the material in transport near the bed in combined sewers. The material appears to be highly heterogeneous both spatially as well as temporally, and is of considerable pollutant potential.
- A model has been obtained which may be used to estimate the transport of the solids comprising, and associated with, the highly polluted material moving near the bed of combined sewers, based on flow conditions, particle characteristics, inputs to the system and upstream sewer characteristics. Although the relationship performs well in Dundee, its wider applicability is still to be tested.
- For the first time a methodology has been proposed which linked the material in transport as near bed solids with the pollution impact of first foul flush in sewers (see section 6.5 "Discussion"). Although the approach is tentative at this stage, with more data its applicability will be increased.

8.6 Future Work

To ease the application of the near bed solids prediction relationship, the tentative relationship observed which related the dry density of material to ambient velocity conditions should be extended. This would enable the methodology to be based solely upon hydraulic and rainfall data. This would mean collecting further data in the Dundee interceptor sewer, or possibly further afield.

Although the relationship obtained for near bed solids transport performed well on the data collected as part of Study 3, on the validation data, and the data collected as part of Study 2, it does not address the fundamental phenomena which controls particle motion near the bed in combined sewers. Indeed given the nature of data collection in live sewers it is difficult to see how this problem may be examined without affecting the mechanisms involved. It may be that further development of the non-intrusive methods (such as fibre optics and the use of ultrasound to monitor solids movement) of monitoring sediment movement in sewers may be the key to understanding the interaction between sewers, sewer sediments and the material moving near the bed (Simons & Sentürk, 1986, Ashley et al., 1992, Ackers et al., 1994 and Wotherspoon, 1994).

The factors which influence the type of material in transport near the bed at different points in sewerage networks must be better isolated to aid understanding of the mode of transport. Again, this would mean further field work.

The interaction between the near bed solids mode of transport and any deposited sediment bed should be investigated. As the deposition and erosion of this material during the DWF pattern is of importance, as when deposited this material is easily eroded by storm flows. This could be done in real sewers using enhanced existing technology developed in Dundee (Wotherspoon, 1994).

Although difficult to collect, data are required regarding the movement of material near the bed in storm conditions in combined sewers. It is in this condition that the material will most closely resemble the 'bed-load' material observed in fluvial hydraulics (Simons & Sentürk, 1986). The mode of transport is important during storms, as it is hypothesised as being the vector for transport of the solids associated with the bulk erosion and/or deposition observed in some combined sewers after storm events (Ashley & Verbanck, 1996).

A methodology should be obtained which can give an accurate estimation of the particle size characteristics of organic solids in transport near the bed, or higher in the flow column. Although a system which performs as well as standard soil sizing techniques on inorganic particles is not envisaged, the classification must be based on some sort of particle sorting (perhaps in solution) by mass . However, any such method would rely, heavily, on retrieval of undisturbed samples.

A test should be developed which could give a better estimation of the specific gravity of individual particles, or discrete groups of particles. The author envisages a test based on the water displacement used in soil mechanics (Smith, 1990).

This study has highlighted a basic problem with sediment research, in that laboratory based sediment transport relationships are generally based on parameters which are virtually impossible to measure accurately in the field, even when part of a dedicated field work programme such as this. Additionally, laboratory oriented studies cannot as yet investigate many of the very important factors which are believed to influence sediment transport in sewers (e.g. upstream sewer conditions, catchment characteristics, sediment supply rates, rainfall history, etc.). If progress is to be made in modelling sediment transport in sewers, the influence which these, often site specific parameters have, must be addressed in further field based studies.

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APPENDIX A : NEAR BED SOLIDS - PHYSICAL CHARACTERISTICS

Table of Contents

Study Site 1 - Dens Brae Trap 1992

Physical Characteristics
Date : 06/07/92

Samp. No.	1	2	3	4	5	6	AVG
Tray No.	1	2	3	4	11	12	
Tray Wt. (g)	761.6	769.0	766.4	767.8	774.6	767.4	
Samp. Vol. (ml)	500.0	520.0	520.0	530.0	540.0	520.0	
Wt Tray + Solids (g)	1514.5	1600.6	1694.5	1467.6	1443.0	1495.7	
Tray + Dry Solids (g)	1456.2	1496.2	1534.4	1380.4	1354.2	1348.2	
Tray + Frncd Slds (g)	1449.5	1485.2	1520.5	1370.8	1342.5	1331.9	
Wet Solids Wt (g)	752.9	831.6	928.1	699.8	668.4	728.3	
Bulk Density (Kg/m^3)	1505.8	1599.2	1784.8	1320.4	1237.8	1400.6	1474.8
Dry Solids Wt (g)	694.6	727.2	768.0	612.6	579.6	580.8	
Frncd Slds Wt (g)	687.9	716.2	754.1	603.0	567.9	564.5	
L.O.D. (%)	7.7	12.6	17.3	12.5	13.3	20.3	13.9
T.D.S. (%)	92.3	87.4	82.7	87.5	86.7	79.7	86.1
MC (%)	8.4	14.4	20.8	14.2	15.3	25.4	16.4
Volatile Solids (%)	1.0	1.5	1.8	1.6	2.0	2.8	1.8
Dry Density (Kg/m^3)	1389.2	1398.5	1476.9	1155.8	1073.3	1116.9	1268.4

Physical Characteristics
Date : 15/07/92

Samp. No.	1	2					AVG
Tray No.	10	3					
Tray Wt. (g)	774.1	765.9					
Samp. Vol. (ml)	500.0	110.0					
Wt Tray + Solids (g)	1532.6	931.9					
Tray + Dry Solids (g)	1331.3	860.9					
Tray + Frncd Slds (g)	1322.5	859.3					
Wet Solids Wt (g)	758.5	166.0					
Bulk Density (Kg/m^3)	1517.0	1509.1					1513.5
Dry Solids Wt (g)	557.2	95.0					
Frncd Slds Wt (g)	548.4	93.4					
L.O.D. (%)	26.5	42.8					34.7
T.D.S. (%)	73.5	57.2					65.3
MC (%)	36.1	74.7					55.4
Volatile Solids (%)	1.6	1.7					1.6
Dry Density (Kg/m^3)	1114.4	863.6					989.0

Physical Characteristics
Date : 21/07/92

Samp. No.	1	2	3	4	5	6	AVG
Tray No.	1	2	8	4	5	6	
Tray Wt. (g)	761.3	768.1	764.0	768.2	756.9	773.3	
Samp. Vol. (ml)	500.0	520.0	420.0	400.0	540.0	520.0	
Wt Tray + Solids (g)	1759.0	1487.5	1575.2	1474.9	1599.9	1691.1	
Tray + Dry Solids (g)	1557.9	1424.5	1409.9	1335.5	1521.6	1556.1	
Tray + Frncd Slds (g)	1537.1	1421.3	1389.5	1328.8	1513.6	1548.6	
Wet Solids Wt (g)	997.7	719.4	811.2	706.7	843.0	917.8	
Bulk Density (Kg/m^3)	1995.4	1383.5	1931.4	1766.8	1561.1	1765.0	1733.8
Dry Solids Wt (g)	796.6	656.4	645.9	567.3	764.7	782.8	
Frncd Slds Wt (g)	775.8	653.2	625.5	560.6	756.7	775.3	
L.O.D. (%)	20.2	8.8	20.4	19.7	9.3	14.7	15.5
T.D.S. (%)	79.8	91.2	79.6	80.3	90.7	85.3	84.5
MC (%)	25.2	9.6	25.6	24.6	10.2	17.2	18.7
Volatile Solids (%)	2.6	0.5	3.2	1.2	1.0	1.0	1.6
Dry Density (Kg/m^3)	1593.2	1262.3	1537.9	1418.3	1416.1	1505.4	1455.5

Physical Characteristics
Date : 27/07/92

Samp. No.	1	2	3	4	5	6	AVG
Tray No.	1	2	3	4	5	6	
Tray Wt. (g)	763.0	768.6	766.2	768.5	765.8	772.4	
Samp. Vol. (ml)	500.0	400.0	500.0	520.0	250.0	100.0	
Wt Tray + Solids (g)	1500.5	1436.5	1564.5	1481.1	1116.3	933.6	
Tray + Dry Solids (g)	1412.5	1323.2	1358.3	1358.3	1019.3	865.4	
Tray + Frncd Slds (g)	1405.3	1320.4	1348.8	1348.8	1017.7	862.7	
Wet Solids Wt (g)	737.5	667.9	798.3	712.6	350.5	161.2	
Bulk Density (Kg/m^3)	1475.0	1669.8	1596.6	1370.4	1402.0	1612.0	1521.0
Dry Solids Wt (g)	649.5	554.6	592.1	589.8	253.5	93.0	
Frncd Slds Wt (g)	642.3	551.8	582.6	580.3	251.9	90.3	
L.O.D. (%)	11.9	17.0	25.8	17.2	27.7	42.3	23.7
T.D.S. (%)	88.1	83.0	74.2	82.8	72.3	57.7	76.3
MC (%)	13.5	20.4	34.8	20.8	38.3	73.3	33.5
Volatile Solids (%)	1.1	0.5	1.6	1.6	0.6	2.9	1.4
Dry Density (Kg/m^3)	1299	1386.5	1184.2	1134.2	1014	930	1158.0

Physical Characteristics
Date : 29/07/92

Samp. No.	1	2	3	4	5	6	AVG
Tray No.	1	2	3	4	5	6	
Tray Wt. (g)	761.5	767.9	766.7	767.8	756.2	771.3	
Samp. Vol. (ml)	500.0	500.0	500.0	150.0	300.0	200.0	
Wt Tray + Solids (g)	1565.2	1416.8	1448.9	976.2	1125.9	1078.4	
Tray + Dry Solids (g)	1395.0	1339.2	1347.6	912.1	995.7	956.2	
Tray + Frncd Slds (g)	1381.5	1320.4	1333.2	904.0	973.6	941.3	
Wet Solids Wt (g)	803.7	648.9	682.2	208.4	369.7	307.1	
Bulk Density (Kg/m^3)	1607.4	1297.8	1364.4	1389.3	1232.3	1535.5	1404.5
Dry Solids Wt (g)	633.5	571.3	580.9	144.3	239.5	184.9	
Frncd Slds Wt (g)	620.0	552.5	566.5	136.2	217.4	170.0	
L.O.D. (%)	21.2	12.0	14.8	30.8	35.2	39.8	25.6
T.D.S. (%)	78.8	88.0	85.2	69.2	64.8	60.2	74.4
MC (%)	26.9	13.6	17.4	44.4	54.4	66.1	37.1
Volatile Solids (%)	2.1	3.3	2.5	5.6	9.2	8.1	5.1
Dry Density (Kg/m^3)	1267	1142.6	1161.8	962	798.3	924.5	1042.7

Physical Characteristics
Date : 12-13/08/92

Samp. No.	1	2	3	4	5	6	AVG
Tray No.	1	2	3	4	5	6	
Tray Wt. (g)	761.1	767.8	765.9	767.4	756.3	770.9	
Samp. Vol. (ml)	500.0	520.0	500.0	535.0	515.0	510.0	
Wt Tray + Solids (g)	1480.7	1506.3	1456.3	1440.7	1363.3	1353.9	
Tray + Dry Solids (g)	1162.3	1161.2	1120.6	1085.0	963.3	1077.6	
Tray + Frncd Slds (g)	1110.4	1102.6	1063.2	976.3	897.7	888.1	
Wet Solids Wt (g)	719.6	738.5	690.4	673.3	607.0	583.0	
Bulk Density (Kg/m^3)	1439.2	1420.2	1380.8	1258.5	1178.6	1143.1	1303.4
Dry Solids Wt (g)	401.2	393.4	354.7	317.6	207.0	306.7	
Frncd Slds Wt (g)	349.3	334.8	297.3	208.9	141.4	117.2	
L.O.D. (%)	44.2	46.7	48.6	52.8	65.9	47.4	51.0
T.D.S. (%)	55.8	53.3	51.4	47.2	34.1	52.6	49.0
MC (%)	79.4	87.7	94.6	112.0	193.2	90.1	109.5
Volatile Solids (%)	12.9	14.9	16.2	34.2	31.7	61.8	28.6

Physical Characteristics
Date : 24-25/08/92

Samp. No.	1	2	3	4	5	6	AVG
Tray No.	7	8	9	10	11	12	
Tray Wt. (g)	767.1	763.8	765.6	774.5	765.5	765.9	
Samp. Vol. (ml)	500.0	90.0	250.0	200.0	200.0	180.0	
Wt Tray + Solids (g)	1625.6	919.6	1220.9	1134.8	1115.4	1096.5	
Tray + Dry Solids (g)	1390.2	876.9	1116.2	1047.8	1060.9	1031.4	
Tray + Frncd Slds (g)	1360.0	873.6	1105.7	1028.6	1048.8	1021.7	
Wet Solids Wt (g)	858.5	155.8	455.3	360.3	349.9	330.6	
Bulk Density (Kg/m^3)	1717.0	1731.1	1821.2	1801.5	1749.5	1836.7	1776.2
Dry Solids Wt (g)	623.1	113.1	350.6	273.3	295.4	265.5	
Frncd Slds Wt (g)	592.9	109.8	340.1	254.1	283.3	255.8	
L.O.D. (%)	27.4	27.4	23.0	24.1	15.6	19.7	22.9
T.D.S. (%)	72.6	72.6	77.0	75.9	84.4	80.3	77.1
MC (%)	37.8	37.8	29.9	31.8	18.4	24.5	30.0
Volatile Solids (%)	4.8	2.9	3.0	7.0	4.1	3.7	4.3
Dry Density (Kg/m^3)	1246.2	1256.7	1402.4	1366.5	1477	1475	1370.6

Physical Characteristics
Date : 08-09/09/92

Samp. No.	1	2	3	4	5	6	AVG
Tray No.	1	2	3	4	5	6	
Tray Wt. (g)	761.8	768.9	767.5	767.5	756.6	771.2	
Samp. Vol. (ml)	520.0	510.0	220.0	500.0	500.0	520.0	
Wt Tray + Solids (g)	1800.9	1545.1	1103.6	1469.4	1487.0	1460.0	
Tray + Dry Solids (g)	1549.6	1111.7	924.4	903.5	983.7	1004.4	
Tray + Frncd Slds (g)	1532.3	1055.9	908.7	841.0	934.7	955.9	
Wet Solids Wt (g)	1039.1	776.2	336.1	701.9	730.4	688.8	
Bulk Density (Kg/m^3)	1998.3	1522.0	1527.7	1403.8	1460.8	1324.6	1539.5
Dry Solids Wt (g)	787.8	342.8	156.9	136.0	227.1	233.2	
Frncd Slds Wt (g)	770.5	287.0	141.2	73.5	178.1	184.7	
L.O.D. (%)	24.2	55.8	53.3	80.6	68.9	66.1	58.2
T.D.S. (%)	75.8	44.2	46.7	19.4	31.1	33.9	41.8
MC (%)	31.9	126.4	114.2	416.1	221.6	195.4	184.3
Volatile Solids (%)	2.2	16.3	10.0	46.0	21.6	20.8	19.5
Dry Density (Kg/m^3)	1515.0	672.2	713.2	272.0	454.2	448.5	679.2

Physical Characteristics
Date : 16-17/09/92

Samp. No.	1	2	3	4	5	6	AVG
Tray No.	7	8	9	10	11	12	
Tray Wt. (g)	767.1	763.1	764.6	773.7	764.6	765.2	
Samp. Vol. (ml)	200.0	200.0	420.0	540.0	510.0	500.0	
Wt Tray + Solids (g)	1156.9	992.3	1303.0	1401.8	1297.8	1330.1	
Tray + Dry Solids (g)	1058.4	847.3	970.9	985.7	982.3	907.0	
Tray + Frncd Slds (g)	1036.8	824.6	931.4	935.3	886.5	835.9	
Wet Solids Wt (g)	389.8	229.2	538.4	628.1	533.2	564.9	
Bulk Density (Kg/m^3)	1949.0	1146.0	1281.9	1163.1	1045.5	1129.8	1285.9
Dry Solids Wt (g)	291.3	84.2	206.3	212.0	217.7	141.8	
Frncd Slds Wt (g)	269.7	61.5	166.8	161.6	121.9	70.7	
L.O.D. (%)	25.3	63.3	61.7	66.2	59.2	74.9	58.4
T.D.S. (%)	74.7	36.7	38.3	33.8	40.8	25.1	41.6
MC (%)	33.8	172.2	161.0	196.3	144.9	298.4	167.8
Volatile Solids (%)	7.4	27.0	19.1	23.8	44.0	50.1	28.6
Dry Density (Kg/m^3)	1456.5	421	491.2	392.6	426.9	283.6	578.6

Study Site 2 - Samuels Trap Project 1993

Bed-Load Sample Data.
DATE : 29.04.93

Samp. No.	1	2	3	4	5	AVG
Tray No.	6	7	8	9	10	
Tray Wt. (g)	770.5	766.8	762.7	764.6	772.3	
Samp. Vol. (ml)	490.0	490.0	500.0	500.0	400.0	476.0
Wt Tray + Solids (g)	1313.9	1306.6	1314.4	1332.1	1188.1	1291.0
Tray + Dry Solids (g)	849.0	834.5	843.5	885.0	825.9	847.6
Tray + Frncd Slds (g)	794.3	788.0	793.2	842.8	791.8	802.0
Wet Solids Wt (g)	543.4	539.8	551.7	567.5	415.8	523.6
Bulk Density Kg/m^3	1109.0	1101.6	1103.4	1135.0	1039.5	1097.7
Dry Solids Wt (g)	78.5	67.7	80.8	120.4	53.6	80.2
Frncd Slds Wt (g)	23.8	21.2	30.5	78.2	19.5	34.6
L.O.D. (%)	85.6	87.5	85.4	78.8	87.1	84.9
T.D.S. (%)	14.4	12.5	14.6	21.2	12.9	15.1
MC (%)	592.2	697.3	582.8	371.3	675.7	583.9
Volatile Solids (%)	69.7	68.7	62.3	35.0	63.6	59.9
Dry Density (Kg/m^3)	160.2	138.2	161.6	240.8	134.0	160.5

Samp. No.	1	2	3	4	5	Totals
Sample Depth (mm)	254.0	127.0	50.8	25.4	12.7	469.9
Bulk Volume (l)	11.43	5.72	2.29	1.14	0.57	21.1
Dry Volume (l)	1.65	0.72	0.33	0.24	0.07	3.0
Volatile Volume (l)	1.15	0.49	0.21	0.08	0.05	2.0

Bed-Load Sample Data.
DATE : 13.05.93

Samp. No.	1	2	AVG
Tray No.	6	7	
Tray Wt. (g)	769.6	766.1	
Samp. Vol. (ml)	500.0	510.0	
Wt Tray + Solids (g)	1322.2	1359.8	1341.0
Tray + Dry Solids (g)	879.8	875.3	877.6
Tray + Frncd Slds (g)	826.9	810.3	818.6
Wet Solids Wt (g)	552.6	593.7	573.2
Bulk Density Kg/m^3	1105.2	1164.1	1134.7
Dry Solids Wt (g)	110.2	109.2	109.7
Frncd Slds Wt (g)	57.3	44.2	50.7
L.O.D. (%)	80.1	81.6	80.8
T.D.S. (%)	19.9	18.4	19.2
MC (%)	401.5	443.7	422.6
Volatile Solids (%)	48.0	59.5	53.8
Dry Density (Kg/m^3)	220.4	214.1	217.3

Samp. No.	1	2	Totals
Sample Depth (mm)	150.0	50.0	200.0
Bulk Volume (l)	6.75	2.25	9.0
Dry Volume (l)	1.35	0.41	1.8
Volatile Volume (l)	0.65	0.25	0.9

Bed-Load Sample Data.
DATE : 19.05.93

Samp. No.	1	2	3	4	5	AVG	BED
Tray No.	6	7	8	9	10		1
Tray Wt. (g)	769.6	766.1	761.6	763.7	771.5		759.0
Samp. Vol. (ml)	500.0	510.0	500.0	500.0	510.0		510.0
Wt Tray + Solids (g)	1322.2	1359.8	1317.7	1380.4	1371.9	1350.4	1594.3
Tray + Dry Solids (g)	879.8	875.3	877.9	983.2	932.6	909.8	1458.1
Tray + Frncd Slds (g)	826.9	810.3	848.8	955.8	910.4	870.4	1377.6
Wet Solids Wt (g)	552.6	593.7	556.1	616.7	600.4	583.9	835.3
Bulk Density (Kg/m^3)	1105.2	1164.1	1112.2	1233.4	1177.3	1158.4	1637.8
Dry Solids Wt (g)	110.2	109.2	116.3	219.5	161.1	143.3	699.1
Frncd Slds Wt (g)	57.3	44.2	87.2	192.1	138.9	103.9	618.6
L.O.D. (%)	80.1	81.6	79.1	64.4	73.2	75.7	16.3
T.D.S. (%)	19.9	18.4	20.9	35.6	26.8	24.3	83.7
MC (%)	401.5	443.7	378.2	181.0	272.7	335.4	19.5
Volatile Solids (%)	48.0	59.5	25.0	12.5	13.8	31.8	11.5
Dry Density (Kg/m^3)	220.4	214.1	232.6	439.0	315.9	266.1	1370.8

Samp. No.	1	2	3	4	5	Totals
Sample Depth (mm)	279.4	152.4	101.6	25.4	25.4	584.2
Bulk Volume (l)	12.57	6.86	4.57	1.14	1.14	26.3
Dry Volume (l)	2.51	1.26	0.96	0.41	0.31	6.40
Volatile Volume (l)	1.20	0.75	0.24	0.05	0.04	2.03

Bed-Load Sample Data.
DATE : 25.05.93

Samp. No.	1	2	3	4	5	AVG	BED
Tray No.	2	3	4	5	6		1
Tray Wt. (g)	766.2	765.0	764.4	754.4	770.4		759.3
Samp. Vol. (ml)	500.0	510.0	510.0	500.0	500.0		500.0
Wt Tray + Solids (g)	1299.0	1275.9	1304.4	1269.8	1272.4	1284.3	1650.0
Tray + Dry Solids (g)	848.3	833.4	947.9	830.5	855.0	863.0	1472.5
Tray + Frncd Slds (g)	793.2	788.5	793.9	785.8	800.1	792.3	1461.8
Wet Solids Wt (g)	532.8	510.9	540.0	515.4	502.0	520.2	890.7
Bulk Density (Kg/m^3)	1065.6	1001.8	1058.8	1030.8	1004.0	1032.2	1781.4
Dry Solids Wt (g)	82.1	68.4	183.5	76.1	84.6	98.9	713.2
Frncd Slds Wt (g)	27.0	23.5	29.5	31.4	29.7	28.2	702.5
L.O.D. (%)	84.6	86.6	66.0	85.2	83.1	81.1	19.9
T.D.S. (%)	15.4	13.4	34.0	14.8	16.9	18.9	80.1
MC (%)	549.0	646.9	194.3	577.3	493.4	492.2	24.9
Volatile Solids (%)	67.1	65.6	83.9	58.7	64.9	68.1	1.5
Dry Density (Kg/m^3)	164.2	134.1	359.8	152.2	169.2	174.3	1426.4

Samp. No.	1	2	3	4	5	Totals
Sample Depth (mm)	127.0	50.8	54.4	12.7	12.7	257.6
Bulk Volume (l)	5.72	2.29	2.45	0.57	0.57	11.6
Dry Volume (l)	0.88	0.31	0.83	0.08	0.10	2.19
Volatile Volume (l)	0.59	0.20	0.70	0.05	0.06	1.49

Bed-Load Sample Data.
DATE : 27.05.93

Samp. No.	1	2	3	4	5	AVG	BED
Tray No.	8	9	10	11	12		7
Tray Wt. (g)	763.3	765.5	772.6	764.4	764.5		767.3
Samp. Vol. (ml)	510.0	520.0	510.0	500.0	500.0		500.0
Wt Tray + Solids (g)	1309.8	1285.4	1307.3	1277.1	1287.3	1293.4	1712.5
Tray + Dry Solids (g)	873.6	841.9	858.7	829.8	855.6	851.9	1508.3
Tray + Frncd Slds (g)	811.9	797.6	802.5	793.5	806.5	802.4	1495.8
Wet Solids Wt (g)	546.5	519.9	534.7	512.7	522.8	527.3	945.2
Bulk Density (Kg/m^3)	1071.6	999.8	1048.4	1025.4	1045.6	1038.2	1890.4
Dry Solids Wt (g)	110.3	76.4	86.1	65.4	91.1	85.9	741.0
Frncd Slds Wt (g)	48.6	32.1	29.9	29.1	42.0	36.3	728.5
M C (%)	79.8	85.3	83.9	87.2	82.6	83.8	21.6
T.D.S. (%)	20.2	14.7	16.1	12.8	17.4	16.2	78.4
Liquid Content (%)	395.5	580.5	521.0	683.9	473.9	531.0	27.6
Volatile Solids (%)	55.9	58.0	65.3	55.5	53.9	57.7	1.7
Dry Density (Kg/m^3)	216.3	146.9	168.8	130.8	182.2	164.5	1482.0

Samp. No.	1	2	3	4	5	Totals
Sample Depth (mm)	203.2	127.0	101.6	50.8	24.5	507.1
Bulk Volume (l)	9.14	5.72	4.57	2.29	1.10	22.8
Dry Volume (l)	1.85	0.84	0.74	0.29	0.19	3.70
Volatile Volume (l)	1.03	0.49	0.48	0.16	0.10	2.14

Study Site 3 - Constable Street Project 1994/1995

Sample Date : 01.03.95

	Samp. No.					
	1	2	3	4	5	6
Tray No.	6	2	10	1	11	4
Empty Tray Wt. (g)	770.2	765.7	770.2	758.4	763.6	764.6
Samp. Volume. (ml)	500	500	500	500	500	500
Samp. + Try Wt (g)	1279.6	1286.7	1290.9	1268.7	1275.7	1282.3
Tray + Dry Solids Wt. (g)	806.5	810.0	826.4	793.9	796.5	807.9
Tray + Frncd Slds Wt. (g)	782.5	785.6	798.1	775.7	778.3	787.1
Wet Solids Wt (g)	509.4	521.0	520.7	510.3	512.1	517.7
Dry Solids Wt (g)	36.3	44.3	56.2	35.5	32.9	43.3
Furnaced Slds Wt (g)	12.3	19.9	27.9	17.3	14.7	22.5
L.O.D. (%)	92.9	91.5	89.2	93.0	93.6	91.6
T.D.S. (%)	7.1	8.5	10.8	7.0	6.4	8.4
MC (%)	1303.3	1076.1	826.5	1337.5	1456.5	1095.6
Volatile Solids (%)	66.1	55.1	50.4	51.3	55.3	48.0
Bulk Density (Kg/m^3)	1019	1042	1041	1021	1024	1035
Specific Gravity	1.02	1.04	1.04	1.02	1.02	1.04
Dry Density (Kg/m^3)	71.4	85.3	108.4	69.7	64.3	83.9
Sample Depth (mm)	160	150	145	140	140	130
Bulk Volume (l)	2.433	2.281	2.205	2.129	2.129	1.977
Bulk Weight (Kg)	2.478	2.376	2.296	2.172	2.180	2.046
Total Dry Weight (g)	173	194	238	148	137	165
Total Inorganic Weight (g)	59	87	118	72	61	86
Total Organic Weight (g)	115	107	120	76	76	79
Fraction of Total Vol. (%)	21.77	20.41	19.73	19.05	19.05	17.69
Fract. of Total Bulk Wt. (%)	21.55	20.66	19.96	18.89	18.95	17.79
Fract. of Tot Inorganics (%)	14.79	21.93	29.74	18.17	15.38	21.63
Fraction of Total Org. (%)	23.26	21.67	24.31	15.40	15.35	16.11

Sample Date : 08.03.95

	Samp. No.					
	1	2	3	4	5	6
Tray No.	3	4	6	8	9	12
Empty Tray Wt. (g)	763.2	763.5	769.0	761.7	762.0	763.9
Samp. Volume. (ml)	1000	820	850	950	1000	820
Samp. + Try Wt (g)	1745.5	1578.2	1618.4	1685.3	1728.0	1571.9
Tray + Dry Solids Wt. (g)	854.8	827.7	840.5	839.0	831.2	816.3
Tray + Frncd Slds Wt. (g)	784.3	780.6	789.2	785.0	778.3	779.4
Wet Solids Wt (g)	982.3	814.7	849.4	923.6	966.0	808.0
Dry Solids Wt (g)	91.6	64.2	71.5	77.3	69.2	52.4
Furnaced Slds Wt (g)	21.1	17.1	20.2	23.3	16.3	15.5
L.O.D. (%)	90.7	92.1	91.6	91.6	92.8	93.5
T.D.S. (%)	9.3	7.9	8.4	8.4	7.2	6.5
MC (%)	972.4	1169.0	1088.0	1094.8	1296.0	1442.0
Volatile Solids (%)	77.0	73.4	71.7	69.9	76.4	70.4
Bulk Density (Kg/m^3)	982	994	999	972	966	985
Specific Gravity	0.98	0.99	1.00	0.97	0.97	0.99
Dry Density (Kg/m^3)	93.1	78.8	84.2	83.5	71.5	64.8
Sample Depth (mm)	175	160	125	135	120	90
Bulk Volume (l)	2.661	2.433	1.901	2.053	1.824	1.368
Bulk Weight (Kg)	2.614	2.417	1.899	1.996	1.762	1.348
Total Dry Weight (g)	248	192	160	172	131	89
Total Inorganic Weight (g)	57	51	45	52	31	26
Total Organic Weight (g)	191	141	115	120	100	62
Fraction of Total Vol. (%)	24.48	22.38	17.48	18.88	16.78	12.59
Fract. of Total Bulk Wt. (%)	24.45	22.61	17.77	18.67	16.49	12.62
Fract. of Tot Inorganics (%)	24.22	21.64	19.15	21.94	13.05	11.12
Fraction of Total Org. (%)	28.66	21.11	17.23	18.01	15.00	9.38

Sample Date : 15.03.95

	Samp. No.					
	1	2	3	4	5	6
Tray No.	2	7	11	5	1	10
Empty Tray Wt. (g)	766.2	765.3	764.5	754.5	759.3	772.3
Samp. Volume. (ml)	1000	1000	500	500	500	500
Samp. + Try Wt (g)	1759.4	1757.5	1270.6	1263.0	1258.9	1277.0
Tray + Dry Solids Wt. (g)	879.1	898.7	811.9	791.0	799.3	820.3
Tray + Frncd Slds Wt. (g)	786.3	784.0	773.3	759.1	770.4	783.9
Wet Solids Wt (g)	993.2	992.2	506.1	508.5	499.6	504.7
Dry Solids Wt (g)	112.9	133.4	47.4	36.5	40.0	48.0
Furnaced Slds Wt (g)	20.1	18.7	8.8	4.6	11.1	11.6
L.O.D. (%)	88.6	86.6	90.6	92.8	92.0	90.5
T.D.S. (%)	11.4	13.4	9.4	7.2	8.0	9.5
MC (%)	779.7	643.8	967.7	1293.2	1149.0	951.5
Volatile Solids (%)	82.2	86.0	81.4	87.4	72.2	75.8
Bulk Density (Kg/m^3)	993	992	1012	1017	999	1009
Specific Gravity	0.99	0.99	1.01	1.02	1.00	1.01
Dry Density (Kg/m^3)	113.6	134.3	93.8	71.9	80.1	95.2
Sample Depth (mm)	150	120	70	65	75	80
Bulk Volume (l)	2.281	1.824	1.064	0.988	1.140	1.216
Bulk Weight (Kg)	2.265	1.810	1.077	1.005	1.139	1.228
Total Dry Weight (g)	259	245	100	71	91	116
Total Inorganic Weight (g)	46	34	19	9	25	28
Total Organic Weight (g)	213	211	81	62	66	88
Fraction of Total Vol. (%)	31.25	25.00	14.58	13.54	15.63	16.67
Fract. of Total Bulk Wt. (%)	31.04	24.81	14.76	13.77	15.61	16.83
Fract. of Tot Inorganics (%)	34.62	25.79	13.88	6.71	19.00	20.97
Fraction of Total Org. (%)	33.66	33.31	12.82	9.79	10.42	13.86

Sample Date :

	Samp. No.					
	1	2	3	4	5	6
Tray No.	3	8	1	6	9	10
Empty Tray Wt. (g)	764.7	762.6	758.7	770.2	763.2	771.6
Samp. Volume. (ml)	1000	1000	1000	1000	950	470
Samp. + Try Wt (g)	1740.2	1728.8	1734.5	1759.8	1709.4	1219.0
Tray + Dry Solids Wt. (g)	889.2	881.2	862.3	871.3	859.8	808.6
Tray + Frncd Slds Wt. (g)	801.3	785.7	784.7	803.5	779.8	781.4
Wet Solids Wt (g)	975.5	966.2	975.8	989.6	946.2	447.4
Dry Solids Wt (g)	124.5	118.6	103.6	101.1	96.6	37.0
Furnaced Slds Wt (g)	36.6	23.1	26.0	33.3	16.6	9.8
L.O.D. (%)	87.2	87.7	89.4	89.8	89.8	91.7
T.D.S. (%)	12.8	12.3	10.6	10.2	10.2	8.3
MC (%)	683.5	714.7	841.9	878.8	879.5	1109.2
Volatile Solids (%)	70.6	80.5	74.9	67.1	82.8	73.5
Bulk Density (Kg/m^3)	976	966	976	990	996	952
Specific Gravity	0.98	0.97	0.98	0.99	1.00	0.95
Dry Density (Kg/m^3)	127.2	122.2	105.9	102.1	102.1	82.4
Sample Depth (mm)	175	145	120	115	100	55
Bulk Volume (l)	2.661	2.205	1.824	1.748	1.520	0.836
Bulk Weight (Kg)	2.596	2.130	1.780	1.730	1.514	0.796
Total Dry Weight (g)	340	271	194	179	155	69
Total Inorganic Weight (g)	100	53	49	59	27	18
Total Organic Weight (g)	240	218	145	120	129	51
Fraction of Total Vol. (%)	26.72	22.14	18.32	17.56	15.27	8.40
Fract. of Total Bulk Wt. (%)	26.62	21.85	18.26	17.75	15.53	8.16
Fract. of Tot Inorganics (%)	34.82	18.39	16.96	20.52	9.31	6.39
Fraction of Total Org. (%)	28.17	25.60	17.05	14.08	15.10	5.97

Sample Date : 29.03.95

	Samp. No.					
	1	2	3	4	5	6
Tray No.	1	2	3	4	5	6
Empty Tray Wt. (g)	759.0	765.7	764.6	764.8	753.9	770.6
Samp. Volume. (ml)	1000	1000	1000	1000	1000	1000
Samp. + Try Wt (g)	1751.3	1751.8	1765.5	1751.5	1754.2	1762.2
Tray + Dry Solids Wt. (g)	876.1	874.9	858.4	863.1	838.1	851.6
Tray + Frncd Slds Wt. (g)	781.0	782.6	780.1	783.0	769.3	784.8
Wet Solids Wt (g)	992.3	986.1	1000.9	986.7	1000.3	991.6
Dry Solids Wt (g)	117.1	109.2	93.8	98.3	84.2	81.0
Furnaced Slds Wt (g)	22.0	16.9	15.5	18.2	15.4	14.2
L.O.D. (%)	88.2	88.9	90.6	90.0	91.6	91.8
T.D.S. (%)	11.8	11.1	9.4	10.0	8.4	8.2
MC (%)	747.4	803.0	967.1	903.8	1088.0	1124.2
Volatile Solids (%)	81.2	84.5	83.5	81.5	81.7	82.5
Bulk Density (Kg/m^3)	992	986	1001	987	1000	992
Specific Gravity	0.99	0.99	1.00	0.99	1.00	0.99
Dry Density (Kg/m^3)	117.9	110.6	93.7	99.5	84.2	81.6
Sample Depth (mm)	185	180	170	150	170	145
Bulk Volume (l)	2.813	2.737	2.585	2.281	2.585	2.205
Bulk Weight (Kg)	2.791	2.699	2.587	2.250	2.585	2.186
Total Dry Weight (g)	332	303	242	227	218	180
Total Inorganic Weight (g)	62	47	40	42	40	32
Total Organic Weight (g)	270	256	202	185	178	149
Fraction of Total Vol. (%)	21.64	21.05	19.88	17.54	19.88	16.96
Fract. of Total Bulk Wt. (%)	21.62	20.90	20.03	17.43	20.02	16.93
Fract. of Tot Inorganics (%)	26.98	20.29	17.32	18.20	17.22	13.66
Fraction of Total Org. (%)	24.71	23.48	18.54	16.97	16.30	13.61

Sample Date : 06.04.95

	Samp. No.					
	1	2	3	4	5	6
Tray No.	7	8	9	10	11	12
Empty Tray Wt. (g)	765.3	762.4	763.1	772.1	763.9	765.3
Samp. Volume. (ml)	1000	1000	1000	1000	1000	1000
Samp. + Try Wt (g)	1787.8	1778.8	1772.2	1795.2	1783.1	1782.6
Tray + Dry Solids Wt. (g)	945.3	847.1	847.4	855.8	851.7	853.0
Tray + Frncd Slds Wt. (g)	788.4	777.7	776.1	788.9	777.9	780.2
Wet Solids Wt (g)	1022.5	1016.4	1009.1	1023.1	1019.2	1017.3
Dry Solids Wt (g)	180.0	84.7	84.3	83.7	87.8	87.7
Furnaced Slds Wt (g)	23.1	15.3	13.0	16.8	14.0	14.9
L.O.D. (%)	82.4	91.7	91.6	91.8	91.4	91.4
T.D.S. (%)	17.6	8.3	8.4	8.2	8.6	8.6
MC (%)	468.1	1100.0	1097.0	1122.3	1060.8	1060.0
Volatile Solids (%)	87.2	81.9	84.6	79.9	84.1	83.0
Bulk Density (Kg/m^3)	1023	1016	1009	1023	1019	1017
Specific Gravity	1.02	1.02	1.01	1.02	1.02	1.02
Dry Density (Kg/m^3)	176.7	83.4	83.6	82.0	86.3	86.3
Sample Depth (mm)	170	175	170	160	170	150
Bulk Volume (l)	2.585	2.661	2.585	2.433	2.585	2.281
Bulk Weight (Kg)	2.643	2.704	2.608	2.489	2.634	2.320
Total Dry Weight (g)	455	222	216	199	223	197
Total Inorganic Weight (g)	58	40	33	40	36	33
Total Organic Weight (g)	397	182	183	159	187	163
Fraction of Total Vol. (%)	20.12	20.71	20.12	18.93	20.12	17.75
Fract. of Total Bulk Wt. (%)	20.21	20.68	19.94	19.03	20.14	17.74
Fract. of Tot Inorganics (%)	28.18	19.33	16.07	19.28	17.14	16.12
Fraction of Total Org. (%)	35.82	16.41	16.50	14.37	16.90	14.74

Sample Date : 12.04.95

	Samp. No.					
	1	2	3	4	5	6
Tray No.	7	8	9	10	11	12
Empty Tray Wt. (g)	765.5	762.2	763	771.9	763.6	764.8
Samp. Volume. (ml)	1000	1000	730	1000	1000	600
Samp. + Try Wt (g)	1788.2	1777.2	1485.7	1770.2	1756.1	1365.2
Tray + Dry Solids Wt. (g)	874.3	861.5	822	874.7	843.3	802.9
Tray + Frncd Slds Wt. (g)	788.4	777.7	776.1	788.9	777.9	780.2
Wet Solids Wt (g)	1022.7	1015.0	722.7	998.3	992.5	600.4
Dry Solids Wt (g)	108.8	99.3	59.0	102.8	79.7	38.1
Furnaced Slds Wt (g)	22.9	15.5	13.1	17.0	14.3	15.4
L.O.D. (%)	89.4	90.2	91.8	89.7	92.0	93.7
T.D.S. (%)	10.6	9.8	8.2	10.3	8.0	6.3
MC (%)	840.0	922.2	1124.9	871.1	1145.3	1475.9
Volatile Solids (%)	79.0	84.4	77.8	83.5	82.1	59.6
Bulk Density (Kg/m^3)	1023	1015	990	998	992	1001
Specific Gravity	1.02	1.02	0.99	1.00	0.99	1.00
Dry Density (Kg/m^3)	106.6	98.0	81.6	103.0	80.3	63.5
Sample Depth (mm)	150	160	95	100	95	85
Bulk Volume (l)	2.281	2.433	1.444	1.520	1.444	1.292
Bulk Weight (Kg)	2.332	2.469	1.430	1.518	1.434	1.293
Total Dry Weight (g)	243	238	118	157	116	82
Total Inorganic Weight (g)	51	37	26	26	21	33
Total Organic Weight (g)	192	201	92	131	95	49
Fraction of Total Vol. (%)	25.00	26.67	15.83	16.67	15.83	14.17
Fract. of Total Bulk Wt. (%)	25.40	26.89	15.57	16.53	15.61	14.08
Fract. of Tot Inorganics (%)	31.70	23.06	16.25	16.07	12.92	20.58
Fraction of Total Org. (%)	26.98	28.29	12.92	18.41	13.41	6.88

Sample Date : 18.04.95

	Samp. No.					
	1	2	3	4	5	6
Tray No.	1	2	3	4	5	6
Empty Tray Wt. (g)	759.1	765.6	764.5	764.8	754.1	770.7
Samp. Volume. (ml)	1000	1000	1000	1000	1000	1000
Samp. + Try Wt (g)	1765	1774.6	1760.7	1785	1773.6	1812.9
Tray + Dry Solids Wt. (g)	855	850.5	850.8	870.5	834.3	890
Tray + Frncd Slds Wt. (g)	781.4	785.8	785	804.5	777.2	828.1
Wet Solids Wt (g)	1005.9	1009.0	996.2	1020.2	1019.5	1042.2
Dry Solids Wt (g)	95.9	84.9	86.3	105.7	80.2	119.3
Furnaced Slds Wt (g)	22.3	20.2	20.5	39.7	23.1	57.4
L.O.D. (%)	90.5	91.6	91.3	89.6	92.1	88.6
T.D.S. (%)	9.5	8.4	8.7	10.4	7.9	11.4
MC (%)	948.9	1088.5	1054.3	865.2	1171.2	773.6
Volatile Solids (%)	76.7	76.2	76.2	62.4	71.2	51.9
Bulk Density (Kg/m^3)	1006	1009	996	1020	1019	1042
Specific Gravity	1.01	1.01	1.00	1.02	1.02	1.04
Dry Density (Kg/m^3)	95.4	84.2	86.6	103.8	78.8	115.0
Sample Depth (mm)	140	120	115	115	100	130
Bulk Volume (l)	2.129	1.824	1.748	1.748	1.520	1.977
Bulk Weight (Kg)	2.141	1.841	1.742	1.784	1.550	2.060
Total Dry Weight (g)	203	154	151	181	120	226
Total Inorganic Weight (g)	47	37	36	68	34	109
Total Organic Weight (g)	156	117	115	113	85	117
Fraction of Total Vol. (%)	23.73	20.34	19.49	19.49	16.95	22.03
Fract. of Total Bulk Wt. (%)	23.64	20.32	19.23	19.69	17.11	22.74
Fract. of Tot Inorganics (%)	21.24	16.44	16.19	30.62	15.50	48.99
Fraction of Total Org. (%)	26.56	19.95	19.69	19.29	14.52	20.02

Sample Date : 26.04.95

	Samp. No.					
	1	2	3	4	5	6
Tray No.	7	8	9	10	11	12
Empty Tray Wt. (g)	765.4	762.5	763.1	772.1	763.9	764.7
Samp. Volume. (ml)	1000	1000	1000	1000	1000	1000
Samp. + Try Wt (g)	1779	1748	1750.3	1758	1770.4	1769.3
Tray + Dry Solids Wt. (g)	868.4	853.4	842.3	846.9	836.1	821.1
Tray + Frncd Slds Wt. (g)	792.9	780	775.7	791.2	779	779.8
Wet Solids Wt (g)	1013.6	985.5	987.2	985.9	1006.5	1004.6
Dry Solids Wt (g)	103.0	90.9	79.2	74.8	72.2	56.4
Furnaced Slds Wt (g)	27.5	17.5	12.6	19.1	15.1	15.1
L.O.D. (%)	89.8	90.8	92.0	92.4	92.8	94.4
T.D.S. (%)	10.2	9.2	8.0	7.6	7.2	5.6
MC (%)	884.1	984.2	1146.5	1218.0	1294.0	1681.2
Volatile Solids (%)	73.3	80.7	84.1	74.5	79.1	73.2
Bulk Density (Kg/m^3)	1014	986	987	986	1007	1005
Specific Gravity	1.01	0.99	0.99	0.99	1.01	1.00
Dry Density (Kg/m^3)	101.8	92.1	80.1	75.8	71.8	56.2
Sample Depth (mm)	140	120	115	115	100	130
Bulk Volume (l)	2.129	1.824	1.748	1.748	1.520	1.977
Bulk Weight (Kg)	2.158	1.798	1.726	1.724	1.530	1.986
Total Dry Weight (g)	216	168	140	133	109	111
Total Inorganic Weight (g)	58	32	22	34	23	30
Total Organic Weight (g)	159	136	118	99	86	81
Fraction of Total Vol. (%)	23.73	20.34	19.49	19.49	16.95	22.03
Fract. of Total Bulk Wt. (%)	24.14	20.12	19.32	19.29	17.13	22.22
Fract. of Tot Inorganics (%)	34.14	19.15	13.19	20.03	13.49	17.56
Fraction of Total Org. (%)	26.54	22.75	19.74	16.53	14.44	13.60

Sample Date : 03.05.95

	Samp. No.					
	1	2	3	4	5	6
Tray No.	1	2	3	4	5	6
Empty Tray Wt. (g)	759.1	765.5	764.3	764.7	754.1	770.6
Samp. Volume. (ml)	1000	700	600	500	600	350
Samp. + Try Wt (g)	1778.5	1456.5	1355.1	1266.4	1358.4	1107.7
Tray + Dry Solids Wt. (g)	859.3	813.6	802.9	792.6	791.2	796.3
Tray + Frncd Slds Wt. (g)	778.1	776.9	773.5	773.4	761.2	776.4
Wet Solids Wt (g)	1019.4	691.0	590.8	501.7	604.3	337.1
Dry Solids Wt (g)	100.2	48.1	38.6	27.9	37.1	25.7
Furnaced Slds Wt (g)	19.0	11.4	9.2	8.7	7.1	5.8
L.O.D. (%)	90.2	93.0	93.5	94.4	93.9	92.4
T.D.S. (%)	9.8	7.0	6.5	5.6	6.1	7.6
MC (%)	917.4	1336.6	1430.6	1698.2	1528.8	1211.7
Volatile Solids (%)	81.0	76.3	76.2	68.8	80.9	77.4
Bulk Density (Kg/m^3)	1019	987	985	1003	1007	963
Specific Gravity	1.02	0.99	0.98	1.00	1.01	0.96
Dry Density (Kg/m^3)	98.5	69.5	65.3	55.6	61.4	76.0
Sample Depth (mm)	100	65	55	45	60	65
Bulk Volume (l)	1.520	0.988	0.836	0.684	0.912	0.988
Bulk Weight (Kg)	1.550	0.976	0.823	0.687	0.919	0.952
Total Dry Weight (g)	149	69	55	38	56	75
Total Inorganic Weight (g)	28	16	13	12	11	17
Total Organic Weight (g)	121	52	42	26	45	58
Fraction of Total Vol. (%)	30.77	20.00	16.92	13.85	18.46	20.00
Fract. of Total Bulk Wt. (%)	31.28	19.69	16.62	13.86	18.55	19.21
Fract. of Tot Inorganics (%)	35.31	20.32	16.23	14.79	13.36	21.19
Fraction of Total Org. (%)	42.24	18.31	14.52	9.13	15.80	20.35

Sample Date : 17.05.95a

	Samp. No.					
	1	2	3	4	5	6
Tray No.	7	8	9	10	11	12
Empty Tray Wt. (g)	765.5	761.7	762.7	771.4	763.2	765
Samp. Volume. (ml)	800	600	470	510	380	200
Samp. + Try Wt (g)	1597.3	1370	1239.9	1283.9	1140.7	971.2
Tray + Dry Solids Wt. (g)	787.8	769.8	791.6	782.4	784.8	776.1
Tray + Frncd Slds Wt. (g)	774.1	765.4	767.7	776.1	766.7	766.6
Wet Solids Wt (g)	831.8	608.3	477.2	512.5	377.5	206.2
Dry Solids Wt (g)	22.3	8.1	28.9	11.0	21.6	11.1
Furnaced Slds Wt (g)	8.6	3.7	5.0	4.7	3.5	1.6
L.O.D. (%)	97.3	98.7	93.9	97.9	94.3	94.6
T.D.S. (%)	2.7	1.3	6.1	2.1	5.7	5.4
MC (%)	3630.0	7409.9	1551.2	4559.1	1647.7	1757.7
Volatile Solids (%)	61.4	54.3	82.7	57.3	83.8	85.6
Bulk Density (Kg/m^3)	1040	1014	1015	1005	993	1031
Specific Gravity	1.04	1.01	1.02	1.00	0.99	1.03
Dry Density (Kg/m^3)	26.8	13.3	60.6	21.5	57.2	53.9
Sample Depth (mm)	140	120	115	115	100	130
Bulk Volume (l)	2.129	1.824	1.748	1.748	1.520	1.977
Bulk Weight (Kg)	2.213	1.850	1.775	1.757	1.510	2.038
Total Dry Weight (g)	57	24	106	38	87	106
Total Inorganic Weight (g)	22	11	18	16	14	15
Total Organic Weight (g)	35	13	88	21	73	91
Fraction of Total Vol. (%)	23.73	20.34	19.49	19.49	16.95	22.03
Fract. of Total Bulk Wt. (%)	24.31	20.31	19.50	19.30	16.59	22.38
Fract. of Tot Inorganics (%)	26.98	13.61	22.46	19.66	17.28	18.81
Fraction of Total Org. (%)	15.23	5.73	38.04	9.34	31.67	39.55

Sample Date : 17.05.95b

	Samp. No.					
	1	2	3	4	5	6
Tray No.	7	8	9	10	11	12
Empty Tray Wt. (g)	766	762	763.4	772.1	763.9	765.1
Samp. Volume. (ml)	680	670	480	300	260	180
Samp. + Try Wt (g)	1414.5	1410.6	1239.7	1054.4	1023.5	946.8
Tray + Dry Solids Wt. (g)	813.3	807.3	791.6	790.4	776	777.3
Tray + Frncd Slds Wt. (g)	774.1	768.3	766.5	773.9	765.1	766
Wet Solids Wt (g)	648.5	648.6	476.3	282.3	259.6	181.7
Dry Solids Wt (g)	47.3	45.3	28.2	18.3	12.1	12.2
Furnaced Slds Wt (g)	8.1	6.3	3.1	1.8	1.2	0.9
L.O.D. (%)	92.7	93.0	94.1	93.5	95.3	93.3
T.D.S. (%)	7.3	7.0	5.9	6.5	4.7	6.7
MC (%)	1271.0	1331.8	1589.0	1442.6	2045.5	1389.3
Volatile Solids (%)	82.9	86.1	89.0	90.2	90.1	92.6
Bulk Density (Kg/m^3)	954	968	992	941	998	1009
Specific Gravity	0.95	0.97	0.99	0.94	1.00	1.01
Dry Density (Kg/m^3)	72.7	69.7	59.2	64.6	46.6	67.2
Sample Depth (mm)	120	120	70	50	45	40
Bulk Volume (l)	1.824	1.824	1.064	0.760	0.684	0.608
Bulk Weight (Kg)	1.740	1.766	1.056	0.715	0.683	0.614
Total Dry Weight (g)	133	127	63	49	32	41
Total Inorganic Weight (g)	23	18	7	5	3	3
Total Organic Weight (g)	110	110	56	44	29	38
Fraction of Total Vol. (%)	29.63	29.63	17.28	12.35	11.11	9.88
Fract. of Total Bulk Wt. (%)	29.19	29.63	17.72	12.00	11.46	10.30
Fract. of Tot Inorganics (%)	41.10	31.96	12.49	8.74	5.70	5.43
Fraction of Total Org. (%)	31.58	31.41	16.06	12.72	8.23	10.83

Sample Date : 13.06.95a

	Samp. No.					
	1	2	3	4	5	6
Tray No.	7	8	9	10	11	12
Empty Tray Wt. (g)	764.94	764.9	754.3	771	765.8	761.9
Samp. Volume. (ml)	1000	1000	1000	560	1000	820
Samp. + Try Wt (g)	1782.8	1777.4	1758.9	1620.5	1754.8	1568.7
Tray + Dry Solids Wt. (g)	837.9	804.1	827.5	820	799.7	787.2
Tray + Frncd Slds Wt. (g)	791.6	782.9	780.8	783.5	779.6	772.2
Wet Solids Wt (g)	1017.9	1012.5	1004.6	849.5	989.0	806.8
Dry Solids Wt (g)	73.0	39.2	73.2	49.0	33.9	25.3
Furnaced Slds Wt (g)	26.7	18.0	26.5	12.5	13.8	10.3
L.O.D. (%)	92.8	96.1	92.7	94.2	96.6	96.9
T.D.S. (%)	7.2	3.9	7.3	5.8	3.4	3.1
MC (%)	1295.1	2482.9	1272.4	1633.7	2817.4	3088.9
Volatile Solids (%)	63.5	54.1	63.8	74.5	59.3	59.3
Bulk Density (Kg/m^3)	1018	1013	1005	1517	989	984
Specific Gravity	1.02	1.01	1.00	1.52	0.99	0.98
Dry Density (Kg/m^3)	71.8	38.7	72.9	58.8	34.3	31.3
Sample Depth (mm)	120	125	110	95	105	90
Bulk Volume (l)	1.824	1.901	1.672	1.444	1.596	1.368
Bulk Weight (Kg)	1.857	1.924	1.680	2.191	1.579	1.346
Total Dry Weight (g)	131	74	122	83	55	43
Total Inorganic Weight (g)	48	34	44	21	22	17
Total Organic Weight (g)	83	40	78	62	32	25
Fraction of Total Vol. (%)	21.62	22.52	19.82	17.12	18.92	16.22
Fract. of Total Bulk Wt. (%)	20.12	20.84	18.20	23.74	17.10	14.58
Fract. of Tot Inorganics (%)	28.24	19.97	26.07	12.56	13.16	10.32
Fraction of Total Org. (%)	28.13	13.49	26.35	21.03	11.00	8.62

Sample Date : 13.06.95b

	Samp. No.					
	1	2	3	4	5	6
Tray No.	9	10	11	12	5	6
Empty Tray Wt. (g)	763.1	771.8	763.6	764.7	754.9	770.3
Samp. Volume. (ml)	1000	1000	1000	1000	1000	1000
Samp. + Try Wt (g)	1751.4	1774.1	1764.1	1764.6	1752.6	1760
Tray + Dry Solids Wt. (g)	825.2	847.1	818.3	825.8	817.2	819.3
Tray + Frncd Slds Wt. (g)	784.5	791.5	782.6	780.4	765.2	779.9
Wet Solids Wt (g)	988.3	1002.3	1000.5	999.9	997.7	989.7
Dry Solids Wt (g)	62.1	75.3	54.7	61.1	62.3	49.0
Furnaced Slds Wt (g)	21.4	19.7	19.0	15.7	10.3	9.6
L.O.D. (%)	93.7	92.5	94.5	93.9	93.8	95.0
T.D.S. (%)	6.3	7.5	5.5	6.1	6.2	5.0
MC (%)	1491.5	1231.1	1729.1	1536.5	1501.4	1919.8
Volatile Solids (%)	65.5	73.8	65.3	74.3	83.5	80.4
Bulk Density (Kg/m^3)	988	1002	1000	1000	998	990
Specific Gravity	0.99	1.00	1.00	1.00	1.00	0.99
Dry Density (Kg/m^3)	62.8	75.1	54.7	61.1	62.4	49.5
Sample Depth (mm)	140	125	130	125	135	110
Bulk Volume (l)	2.129	1.901	1.977	1.901	2.053	1.672
Bulk Weight (Kg)	2.104	1.905	1.978	1.900	2.048	1.655
Total Dry Weight (g)	134	143	108	116	128	83
Total Inorganic Weight (g)	46	37	38	30	21	16
Total Organic Weight (g)	88	105	71	86	107	67
Fraction of Total Vol. (%)	21.37	19.08	19.85	19.08	20.61	16.79
Fract. of Total Bulk Wt. (%)	21.18	19.17	19.91	19.13	20.61	16.66
Fract. of Tot Inorganics (%)	26.80	21.72	21.82	17.35	12.32	9.43
Fraction of Total Org. (%)	19.19	23.08	15.44	18.89	23.41	14.57

Sample Date : 20.06.93a

	Samp. No.					
	1	2	3	4	5	6
Tray No.	10	11	12			
Empty Tray Wt. (g)	772.3	764.3	765			
Samp. Volume. (ml)	700	190	130			
Samp. + Try Wt (g)	1451.8	950.1	894.4			
Tray + Dry Solids Wt. (g)	835.6	779.8	776			
Tray + Frncd Slds Wt. (g)	787.7	767.7	766.5			
Wet Solids Wt (g)	679.5	185.8	129.4			
Dry Solids Wt (g)	63.3	15.5	11.0			
Furnaced Slds Wt (g)	15.4	3.4	1.5			
L.O.D. (%)	90.7	91.7	91.5			
T.D.S. (%)	9.3	8.3	8.5			
MC (%)	973.5	1098.7	1076.4			
Volatile Solids (%)	75.7	78.1	86.4			
Bulk Density (Kg/m^3)	971	978	995			
Specific Gravity	0.97	0.98	1.00			
Dry Density (Kg/m^3)	92.9	83.3	85.0			
Sample Depth (mm)	100	40	40			
Bulk Volume (l)	1.520	0.608	0.608			
Bulk Weight (Kg)	1.476	0.595	0.605			
Total Dry Weight (g)	142	51	52			
Total Inorganic Weight (g)	34	11	7			
Total Organic Weight (g)	107	40	45			
Fraction of Total Vol. (%)	55.56	22.22	22.22			
Fract. of Total Bulk Wt. (%)	55.15	22.22	22.62			
Fract. of Tot Inorganics (%)	65.46	21.14	13.39			
Fraction of Total Org. (%)	55.99	20.69	23.32			

Sample Date : 20.06.95b

	Samp. No.					
	1	2	3	4	5	6
Tray No.	3	5	6	7	8	9
Empty Tray Wt. (g)	765	754.4	770.3	766.2	762.3	763.3
Samp. Volume. (ml)	1000	1000	880	900	450	400
Samp. + Try Wt (g)	1763.6	1753.3	1644.5	1649.8	1204.6	1165
Tray + Dry Solids Wt. (g)	924.9	906.6	901.7	876.5	796.4	810.2
Tray + Frncd Slds Wt. (g)	784.5	791.5	782.6	780.4	765.2	779.9
Wet Solids Wt (g)	998.6	998.9	874.2	883.6	442.3	401.7
Dry Solids Wt (g)	159.9	152.2	131.4	110.3	34.1	46.9
Furnaced Slds Wt (g)	19.5	37.1	12.3	14.2	2.9	16.6
L.O.D. (%)	84.0	84.8	85.0	87.5	92.3	88.3
T.D.S. (%)	16.0	15.2	15.0	12.5	7.7	11.7
MC (%)	524.5	556.3	565.3	701.1	1197.1	756.5
Volatile Solids (%)	87.8	75.6	90.6	87.1	91.5	64.6
Bulk Density (Kg/m^3)	999	999	993	982	983	1004
Specific Gravity	1.00	1.00	0.99	0.98	0.98	1.00
Dry Density (Kg/m^3)	160.1	152.3	150.2	124.5	77.0	116.8
Sample Depth (mm)	160	160	140	130	70	80
Bulk Volume (l)	2.433	2.433	2.129	1.977	1.064	1.216
Bulk Weight (Kg)	2.429	2.430	2.115	1.941	1.046	1.221
Total Dry Weight (g)	390	371	320	247	82	142
Total Inorganic Weight (g)	48	90	30	32	7	50
Total Organic Weight (g)	342	280	290	215	75	92
Fraction of Total Vol. (%)	24.24	24.24	21.21	19.70	10.61	12.12
Fract. of Total Bulk Wt. (%)	24.39	24.40	21.23	19.48	10.50	12.26
Fract. of Tot Inorganics (%)	23.00	43.74	14.50	15.38	3.38	24.34
Fraction of Total Org. (%)	28.45	23.31	24.12	17.88	6.24	7.63

Sample Date : 27.06.95

	Samp. No.					
	1	2	3	4	5	6
Tray No.	7	9	11	8	12	10
Empty Tray Wt. (g)	766.5	763.5	763.9	762.3	764.8	772.3
Samp. Volume. (ml)	1000	1000	1000	830	1000	760
Samp. + Try Wt (g)	1759.7	1788.2	1772.2	1595.4	1762.7	1533.3
Tray + Dry Solids Wt. (g)	906.1	889.1	872.7	844.8	854.9	838.5
Tray + Frncd Slds Wt. (g)	800.7	792.3	789	778.6	784	784.5
Wet Solids Wt (g)	993.2	1024.7	1008.3	833.1	997.9	761.0
Dry Solids Wt (g)	139.6	125.6	108.8	82.5	90.1	66.2
Furnaced Slds Wt (g)	34.2	28.8	25.1	16.3	19.2	12.2
L.O.D. (%)	85.9	87.7	89.2	90.1	91.0	91.3
T.D.S. (%)	14.1	12.3	10.8	9.9	9.0	8.7
MC (%)	611.5	715.8	826.7	909.8	1007.5	1049.5
Volatile Solids (%)	75.5	77.1	76.9	80.2	78.7	81.6
Bulk Density (Kg/m^3)	993	1025	1008	1004	998	1001
Specific Gravity	0.99	1.02	1.01	1.00	1.00	1.00
Dry Density (Kg/m^3)	140.4	122.9	108.0	99.1	90.3	87.0
Sample Depth (mm)	165	165	155	150	150	115
Bulk Volume (l)	2.509	2.509	2.357	2.281	2.281	1.748
Bulk Weight (Kg)	2.492	2.571	2.376	2.289	2.276	1.751
Total Dry Weight (g)	353	307	254	226	206	152
Total Inorganic Weight (g)	86	71	59	45	44	28
Total Organic Weight (g)	266	237	196	181	162	124
Fraction of Total Vol. (%)	21.02	21.02	19.75	19.11	19.11	14.65
Fract. of Total Bulk Wt. (%)	20.76	21.42	19.80	19.07	18.96	14.59
Fract. of Tot Inorganics (%)	28.41	23.19	19.29	14.68	14.43	9.22
Fraction of Total Org. (%)	25.55	22.74	18.77	17.39	15.55	11.91

Sample Date : 17.07.95a

	Samp. No.					
	1	2	3	4	5	6
Tray No.	5	12				
Empty Tray Wt. (g)	754.4	764.7				
Samp. Volume. (ml)	130	460				
Samp. + Try Wt (g)	892.6	1192.1				
Tray + Dry Solids Wt. (g)	766.3	783.6				
Tray + Frncd Slds Wt. (g)	756.5	767.4				
Wet Solids Wt (g)	138.2	427.4				
Dry Solids Wt (g)	11.9	18.9				
Furnaced Slds Wt (g)	2.1	2.7				
L.O.D. (%)	91.4	95.6				
T.D.S. (%)	8.6	4.4				
MC (%)	1061.3	2161.4				
Volatile Solids (%)	82.4	85.7				
Bulk Density (Kg/m^3)	1063	929				
Specific Gravity	1.06	0.93				
Dry Density (Kg/m^3)	86.5	44.1				
Sample Depth (mm)	45	130				
Bulk Volume (l)	0.684	1.977				
Bulk Weight (Kg)	0.727	1.836				
Total Dry Weight (g)	59	87				
Total Inorganic Weight (g)	10	12				
Total Organic Weight (g)	49	75				
Fraction of Total Vol. (%)	25.71	74.29				
Fract. of Total Bulk Wt. (%)	28.37	71.63				
Fract. of Tot Inorganics (%)	45.43	54.57				
Fraction of Total Org. (%)	39.31	60.69				

Sample Date : 17.07.95b

	Samp. No.					
	1	2	3	4	5	6
Tray No.	7	8	3	6	11	9
Empty Tray Wt. (g)	766.4	762.4	765	770.2	763.9	763.2
Samp. Volume. (ml)	680	400	250	280	250	240
Samp. + Try Wt (g)	1454	1174.1	1018.8	1036.5	1022.3	1008.2
Tray + Dry Solids Wt. (g)	816.4	793.7	782.6	788	779.3	771.9
Tray + Frncd Slds Wt. (g)	786.8	768.1	769.1	772.8	766.2	763.7
Wet Solids Wt (g)	687.6	411.7	253.8	266.3	258.4	245.0
Dry Solids Wt (g)	50.0	31.3	17.6	17.8	15.4	8.7
Furnaced Slds Wt (g)	20.4	5.7	4.1	2.6	2.3	0.5
L.O.D. (%)	92.7	92.4	93.1	93.3	94.0	96.4
T.D.S. (%)	7.3	7.6	6.9	6.7	6.0	3.6
MC (%)	1275.2	1215.3	1342.0	1396.1	1577.9	2716.1
Volatile Solids (%)	59.2	81.8	76.7	85.4	85.1	94.3
Bulk Density (Kg/m^3)	1011	1029	1015	951	1034	1021
Specific Gravity	1.01	1.03	1.02	0.95	1.03	1.02
Dry Density (Kg/m^3)	72.8	76.2	69.4	66.6	59.7	35.5
Sample Depth (mm)	135	95	70	60	50	50
Bulk Volume (l)	2.053	1.444	1.064	0.912	0.760	0.760
Bulk Weight (Kg)	2.075	1.487	1.080	0.868	0.786	0.776
Total Dry Weight (g)	149.3	109.8	73.8	61.0	45.3	27.0
Total Inorganic Weight (g)	60.9	20.0	17.2	8.9	6.8	1.6
Total Organic Weight (g)	88.4	89.8	56.6	52.1	38.5	25.4
Fraction of Total Vol. (%)	32.93	23.17	17.07	14.63	12.20	12.20
Fract. of Total Bulk Wt. (%)	32.97	23.61	17.16	13.78	12.48	12.33
Fract. of Tot Inorganics (%)	53.53	17.58	15.11	7.83	5.95	1.36
Fraction of Total Org. (%)	27.15	27.60	17.40	16.00	11.84	7.82

Sample Date : 26.07.95

	Samp. No.					
	1	2	3	4	5	6
Tray No.	1	2	3	4	5	6
Empty Tray Wt. (g)	758.7	765.9	765.3	764.6	754.5	770.4
Samp. Volume. (ml)	640	700	310	360	750	190
Samp. + Try Wt (g)	1377.8	1458.1	1070.9	1118.2	1503.3	953.1
Tray + Dry Solids Wt. (g)	819.7	824.8	794.1	784	799.9	787.3
Tray + Frncd Slds Wt. (g)	765.3	775.5	770.2	768.7	760.4	772.2
Wet Solids Wt (g)	619.1	692.2	305.6	353.6	748.8	182.7
Dry Solids Wt (g)	61.0	58.9	28.8	19.4	45.4	16.9
Furnaced Slds Wt (g)	6.6	9.6	4.9	4.1	5.9	1.8
L.O.D. (%)	90.1	91.5	90.6	94.5	93.9	90.7
T.D.S. (%)	9.9	8.5	9.4	5.5	6.1	9.3
MC (%)	914.9	1075.2	961.1	1722.7	1549.3	981.1
Volatile Solids (%)	89.2	83.7	83.0	78.9	87.0	89.3
Bulk Density (Kg/m^3)	967	989	986	982	998	962
Specific Gravity	0.97	0.99	0.99	0.98	1.00	0.96
Dry Density (Kg/m^3)	98.2	85.0	94.1	54.8	60.6	92.2
Sample Depth (mm)	180	140	105	110	100	70
Bulk Volume (l)	2.737	2.129	1.596	1.672	1.520	1.064
Bulk Weight (Kg)	2.647	2.105	1.574	1.643	1.518	1.023
Total Dry Weight (g)	269.6	181.1	150.4	91.8	92.2	98.4
Total Inorganic Weight (g)	29.2	29.5	25.6	19.4	12.0	10.5
Total Organic Weight (g)	240.5	151.6	124.9	72.4	80.2	88.0
Fraction of Total Vol. (%)	28.35	22.05	16.54	17.32	15.75	11.02
Fract. of Total Bulk Wt. (%)	27.91	22.19	16.59	17.32	16.00	10.79
Fract. of Tot Inorganics (%)	25.22	25.52	22.13	16.77	10.36	9.07
Fraction of Total Org. (%)	35.92	22.64	18.65	10.81	11.98	13.14

Sample Date : 27.07.95

	Samp. No.					
	1	2	3	4	5	6
Tray No.	7	8	9	10	11	12
Empty Tray Wt. (g)	767	762.9	763.2	773.6	763.7	764.9
Samp. Volume. (ml)	600	330	230	200	180	90
Samp. + Try Wt (g)	1355.2	1092.5	988.5	964.6	941.6	851.6
Tray + Dry Solids Wt. (g)	801.7	776.1	773.2	778	773.6	768
Tray + Frncd Slds Wt. (g)	769.5	764.5	764.2	773.8	764.7	765.3
Wet Solids Wt (g)	588.2	329.6	225.3	191.0	177.9	86.7
Dry Solids Wt (g)	34.7	13.2	10.0	4.4	9.9	3.1
Furnaced Slds Wt (g)	2.5	1.6	1.0	0.2	1.0	0.4
L.O.D. (%)	94.1	96.0	95.6	97.7	94.4	96.4
T.D.S. (%)	5.9	4.0	4.4	2.3	5.6	3.6
MC (%)	1595.1	2397.0	2153.0	4240.9	1697.0	2696.8
Volatile Solids (%)	92.8	87.9	90.0	95.5	89.9	87.1
Bulk Density (Kg/m^3)	980	999	980	955	988	963
Specific Gravity	0.98	1.00	0.98	0.96	0.99	0.96
Dry Density (Kg/m^3)	58.9	40.0	44.3	23.0	55.6	35.7
Sample Depth (mm)	120	75	45	30	30	15
Bulk Volume (l)	1.824	1.140	0.684	0.456	0.456	0.228
Bulk Weight (Kg)	1.789	1.139	0.670	0.436	0.451	0.220
Total Dry Weight (g)	107.63	45.67	30.37	10.51	25.38	8.15
Total Inorganic Weight (g)	7.75	5.54	3.04	0.48	2.56	1.05
Total Organic Weight (g)	99.88	40.13	27.33	10.03	22.82	7.10
Fraction of Total Vol. (%)	40.00	25.00	15.00	10.00	10.00	5.00
Fract. of Total Bulk Wt. (%)	39.89	25.40	14.95	9.71	10.05	4.90
Fract. of Tot Inorganics (%)	40.04	28.58	15.68	2.47	13.24	5.43
Fraction of Total Org. (%)	49.89	20.05	13.65	5.01	11.40	3.55

APPENDIX B : INORGANIC PARTICLE SIZE DISTRIBUTION

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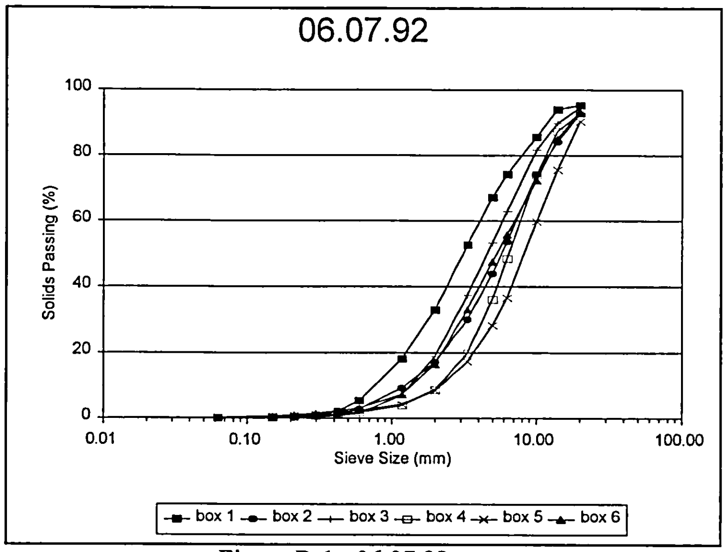
Study Site 1 - Dens Brae Trap



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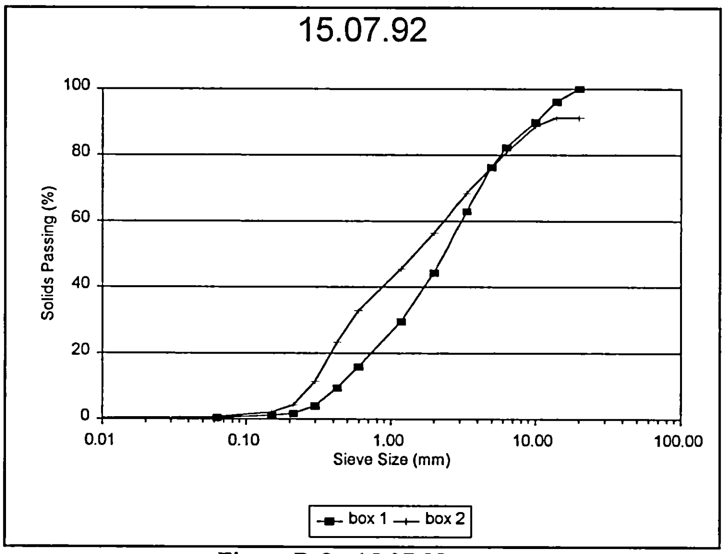

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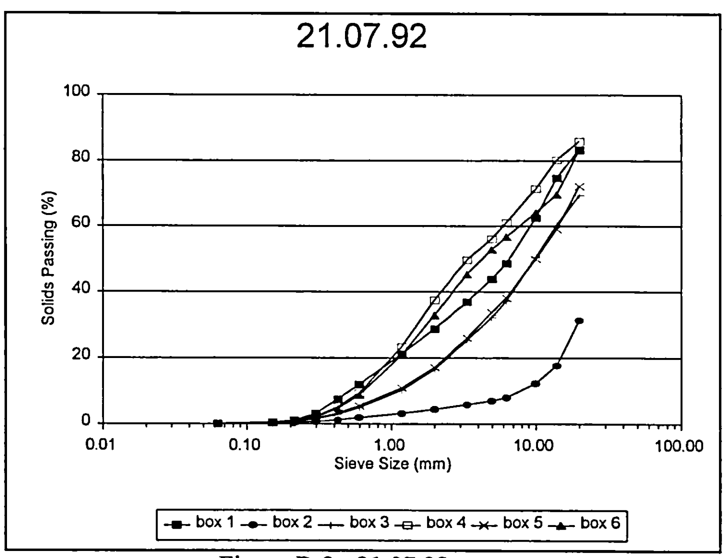

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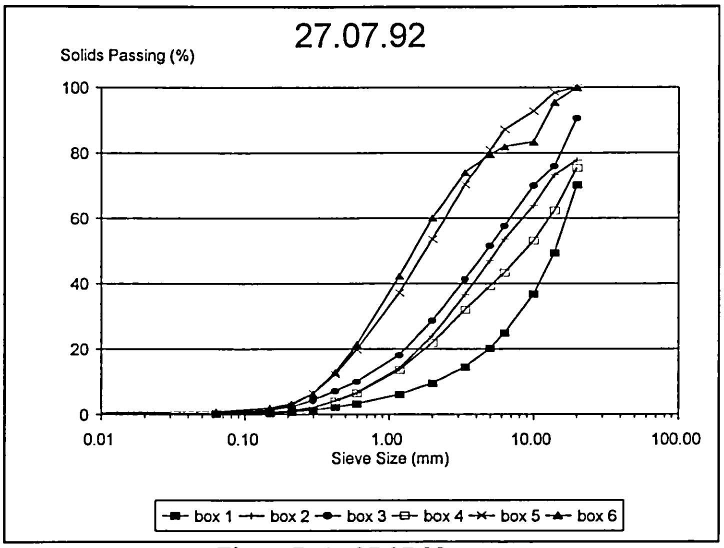

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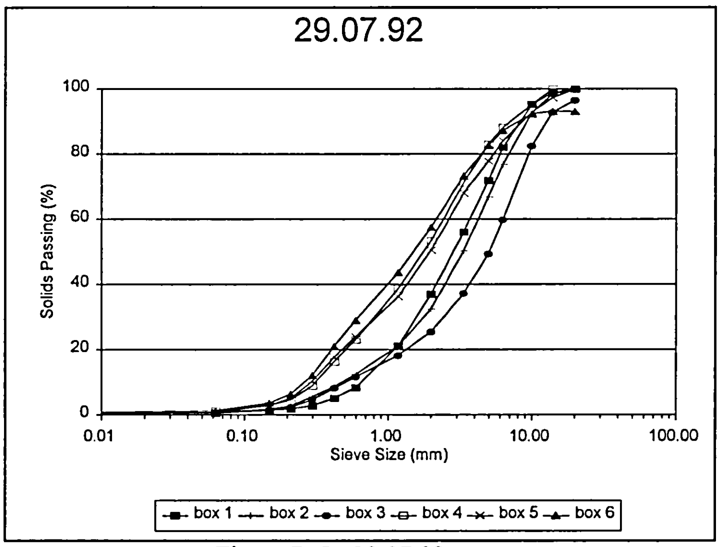

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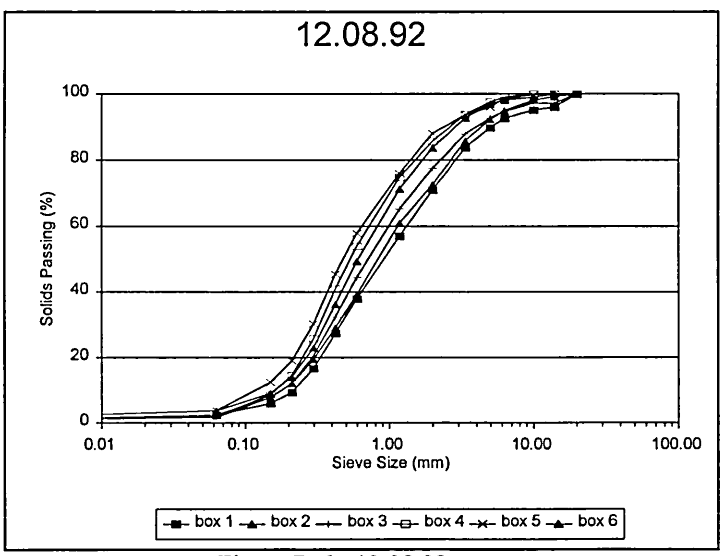

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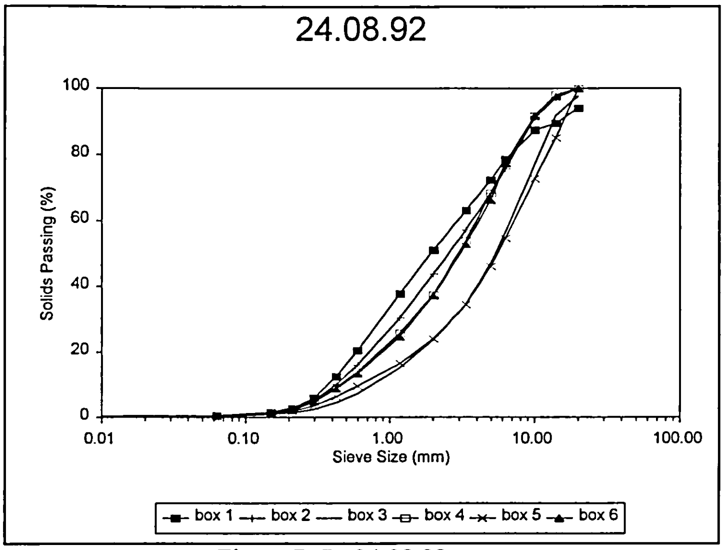

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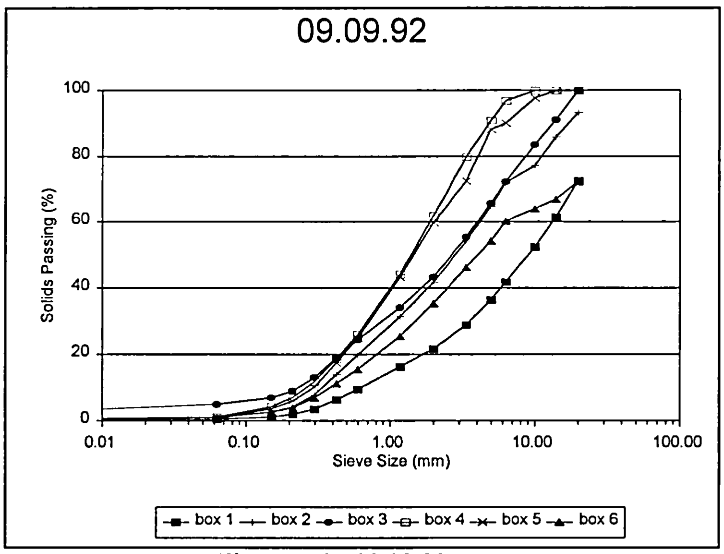

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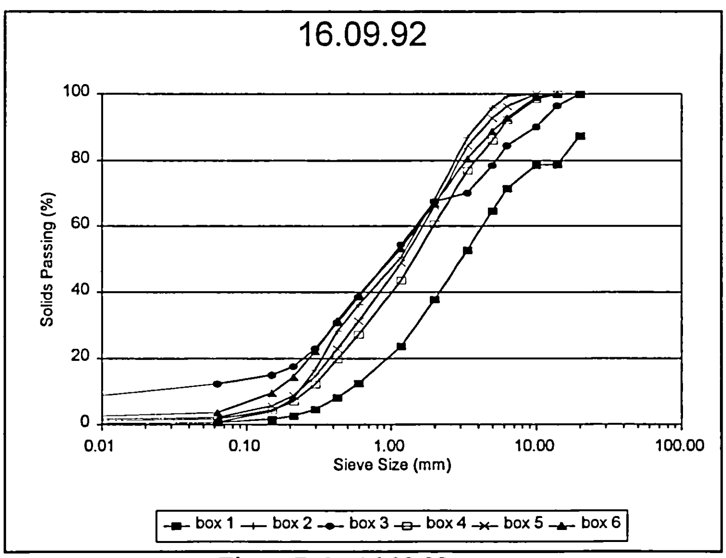

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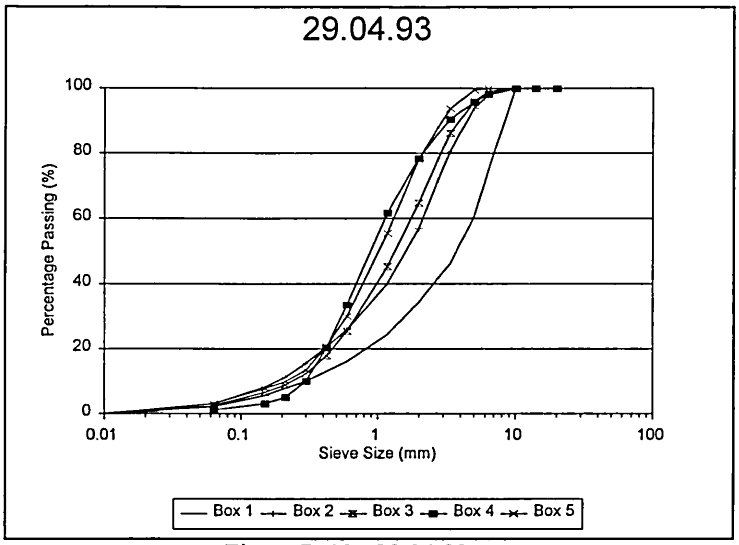

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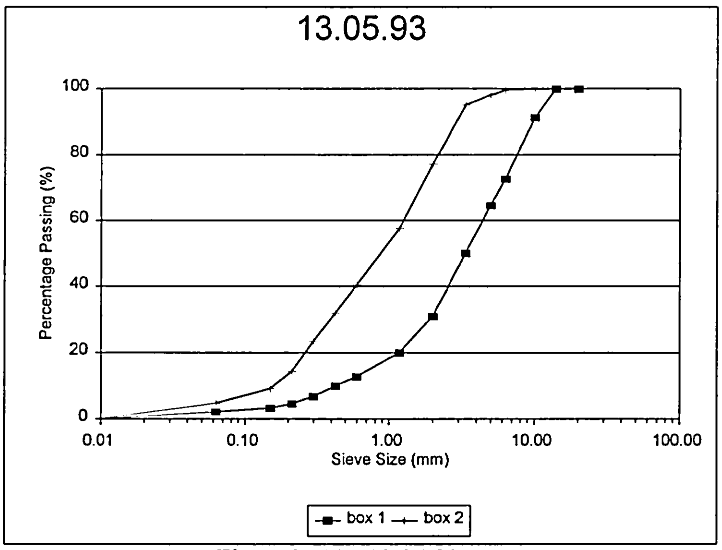

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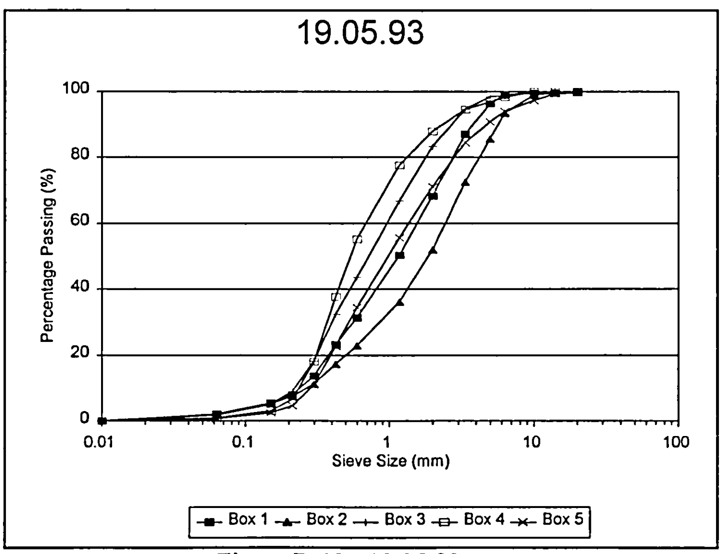

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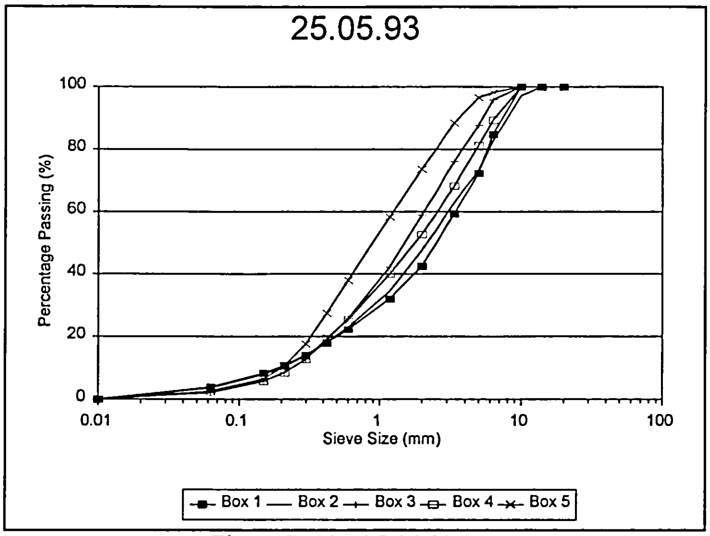

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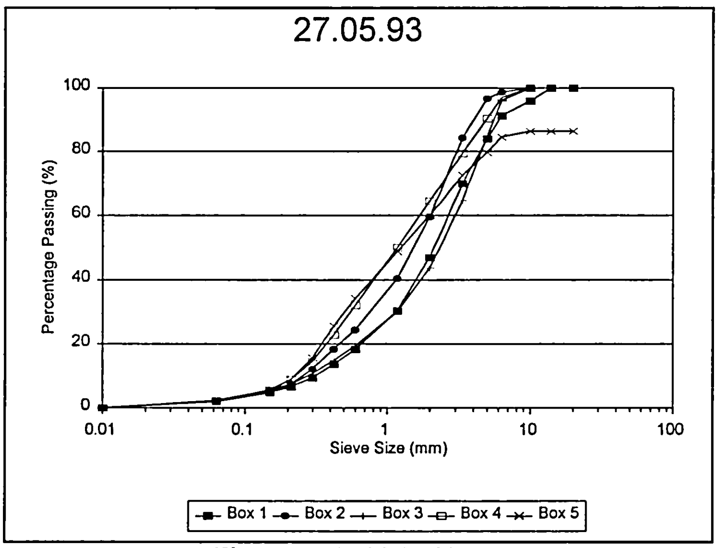

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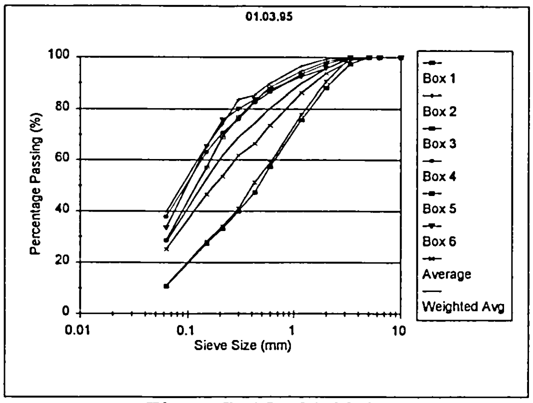

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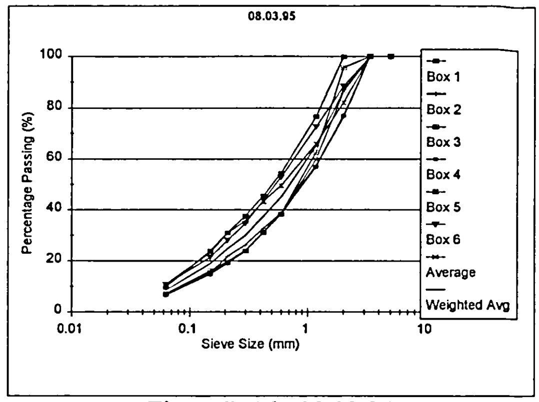

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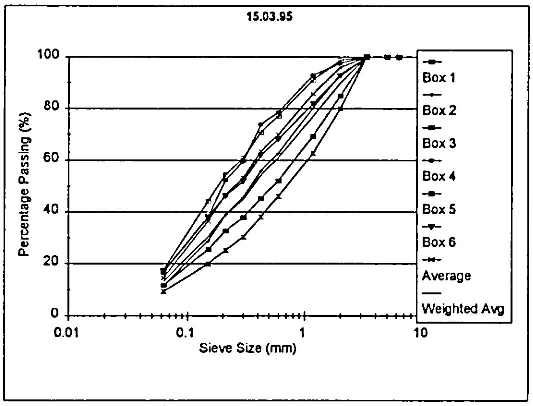

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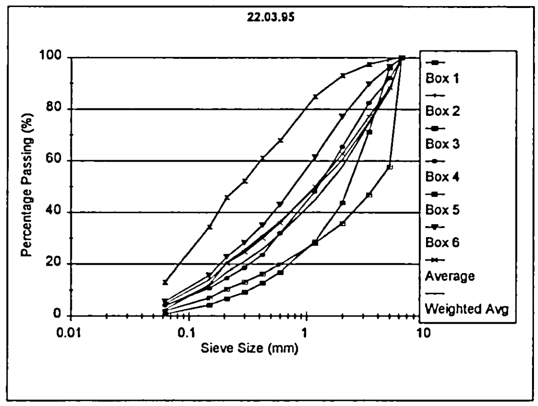

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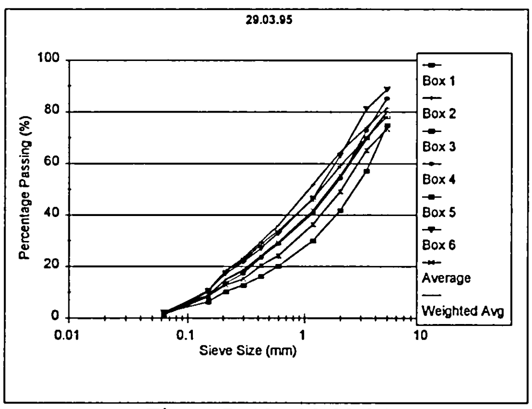

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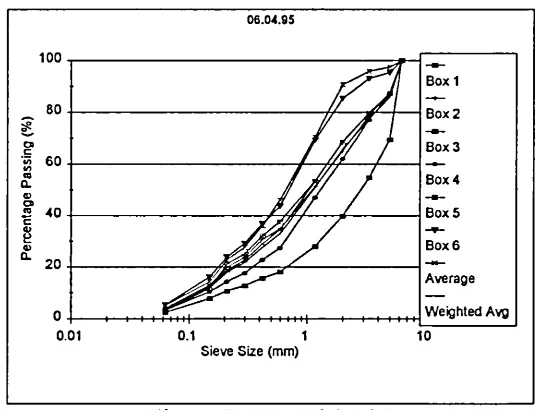

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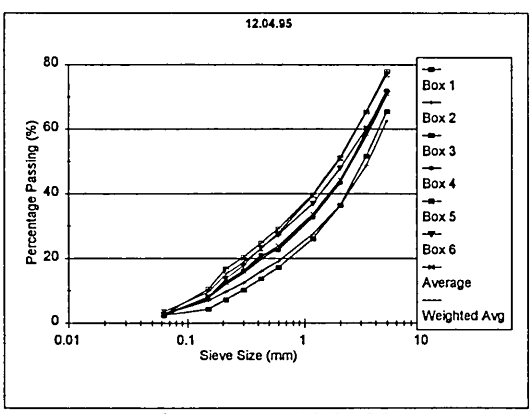

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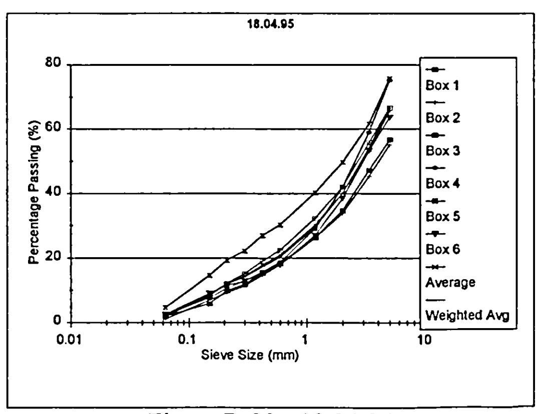

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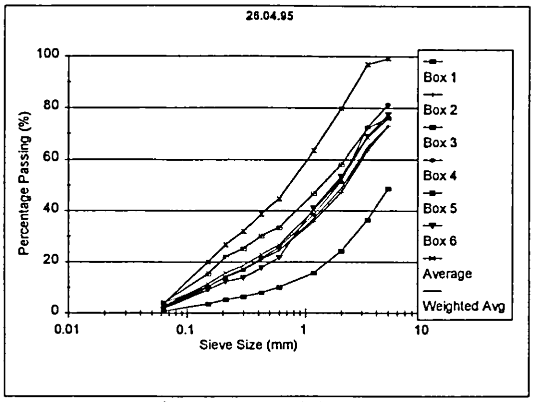

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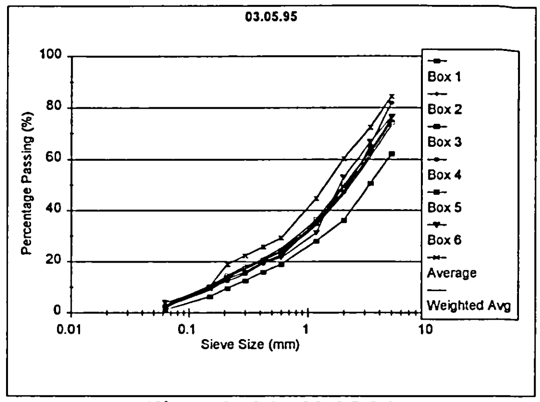

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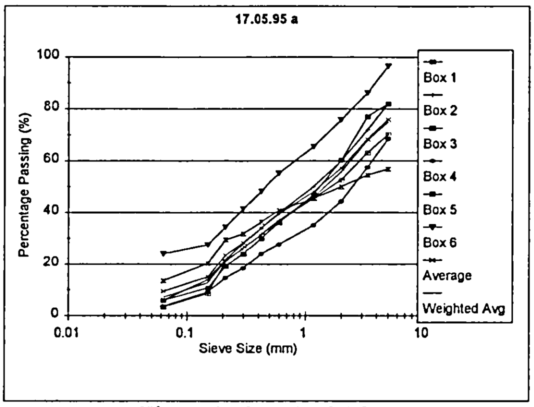

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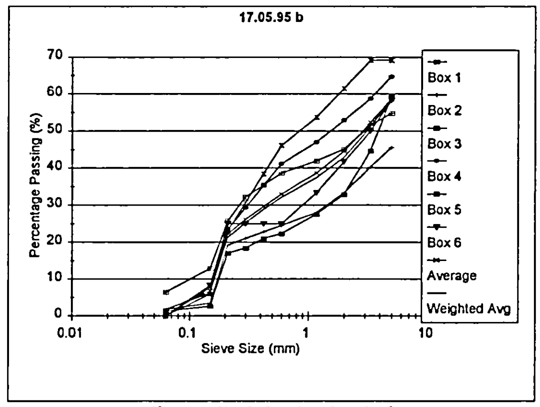

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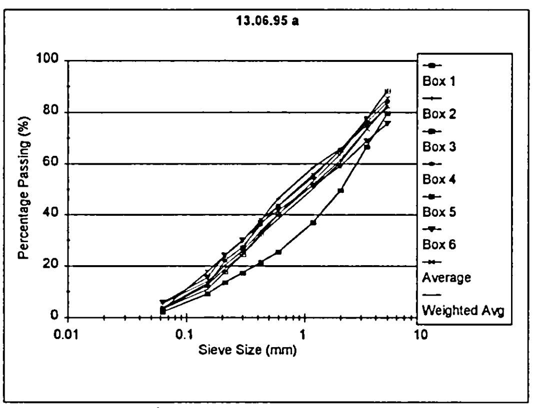

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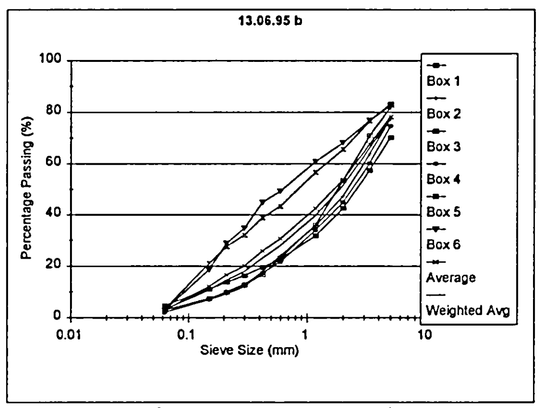

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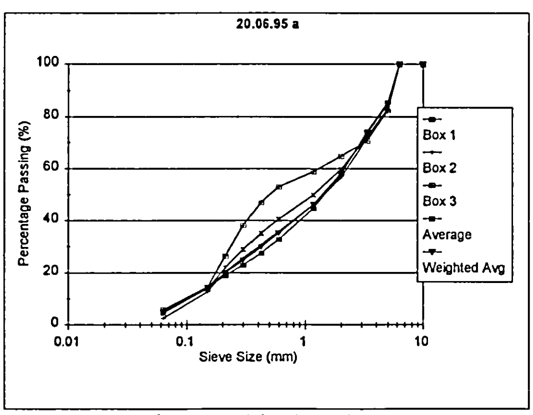

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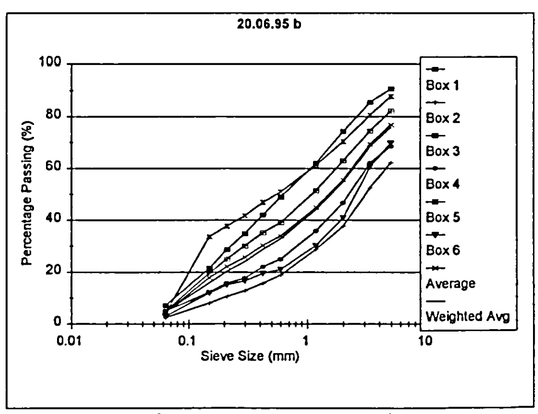

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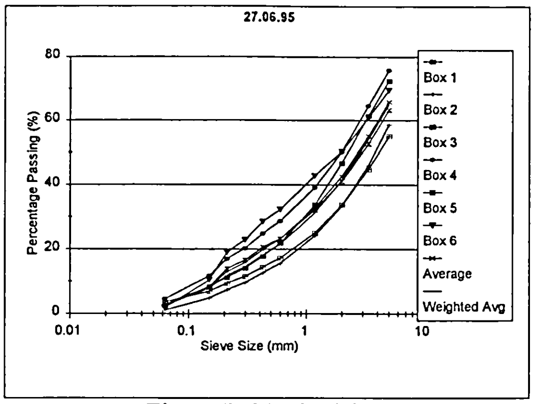

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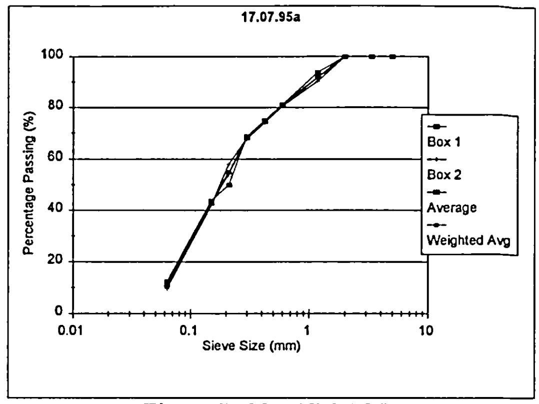

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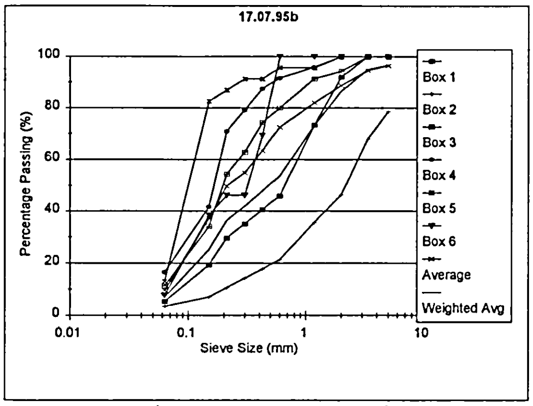

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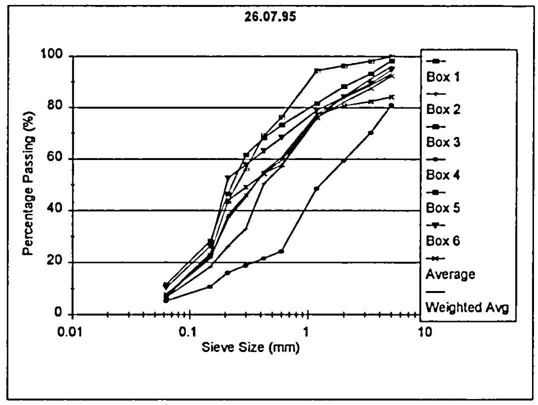

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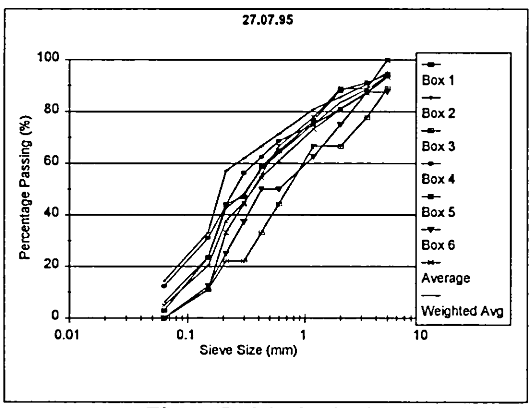

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APPENDIX C : SETTLING VELOCITY TESTING

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C.1 Introduction Error! Bookmark not defined.

Idealistically, the transport of any sediment particle by a flow is dependent on the properties of the flow and the characteristics of the material in transport. In characterising a particle, important parameters are recognised as being; shape, relative density and size, the cumulative effect of which can be represented in the settling velocity of a particulate. The settling velocity is, therefore, important in the prediction of solids transport, and also influences the design of ancillary structures within sewerage systems and treatment plants.

The predominately inorganic sediment deposits within sewerage systems, in general, contain particles ranging in size from silts and clays up to cobbles, and therefore cover a wide range of settling velocities. Material in transport as suspended load will have a very different range of settling velocities, due to the predominately fine organic nature of this material. The material in transport at the bed will vary between these two extremes, depending on ambient flows and sediment supply characteristics.

Currently, there are a number of different research establishments using differing methodologies for estimating settling velocities of sewer sediments and estuarine muds (Owen, 1976, Burt et al., 1991, Chebbo, 1992, Michelbach & Wöhrle, 1992a, Michelbach & Wöhrle, 1992b, Tyack et al., 1995 and Aiguier et al., 1995). Comparative studies have recognised variations in the results obtained from these methodologies (Wotherspoon, 1994 and Aiguier et al, 1995). Delo (1988 and 1991) in a study of settling velocity characteristics of cohesive estuarine sediments recognised the following influencing factors;

- Measurement of the settling velocity of flocculated sediment must be undertaken in as near to site conditions as possible.
- Settling velocity of cohesive sediments is dependant on sediment concentration, with average fall velocities increasing at higher concentrations, unless the concentration is so high that hindered settling occurs.
- Settling velocities for material obtained from different locations may vary considerably.
- There may be a considerable range of settling velocities within any given sample.
- Hindered settling of particles in high concentration may result in a reduction of the average settling velocity.

C.2 Available Methods

This section will give an overview of the different settling velocity tests commonly employed, and highlight any drawbacks. It will not, however, give details of individual test methodologies. For most methods available, the results are in the form of a settling velocity distribution curve for the sample being tested. Particles are typically allowed to settle for progressively longer time steps. The cumulative mass of material settling out of suspension in each time step is then plotted against the fall velocity of the time step considered to give a distribution curve.

A number of methodologies are suited practically to the estimation of the settling velocity of the material in transport and deposited in sewers as part of this study;

C.2.1 Owen Tube Apparatus (Owen 1975)

This method was developed in estuarine studies and offers a means of obtaining and testing samples in-situ, avoiding errors caused by the effects of storage. The methodology has been employed as part of previous studies in Dundee (Wotherspoon, 1994). The results obtained by Wotherspoon were considerably lower than that obtained by other researchers (0.04mm/s compared with 0.09 - 0.8mm/s) using different methods. This being attributed to the manner in which samples of settled solids are obtained from the apparatus.

C.2.2 Multi-Port Column (Pisano, 1995)

This method has been widely adopted in the U.S.A. and Canada, for determination of settlement velocities for the design of sewage treatment processes.

C.2.3 Scottish Development Department (SDD) Method (SDD, 1980)

Research into the performance of storm sewage overflows resulted in a requirement to examine the rise and fall characteristics of sediment particulates in the wastewater. The apparatus used is illustrated in Figure C.1. This methodology is not suitable where the flocs are observed to form in the sample, and as such is more applicable to th predominately inorganic samples experienced in storm sewers

C.2.4 French Method (Chebbo, 1992 and Aiguier et al, 1995)

Using this method particles above 50μm are tested using a settling column, and the settling velocity of particles below 50μm using an Andréasen Pipette.

Particles are separated by wet sieving, this process may result in a reduction of the particle size, and hence reducing the measured settling velocities.

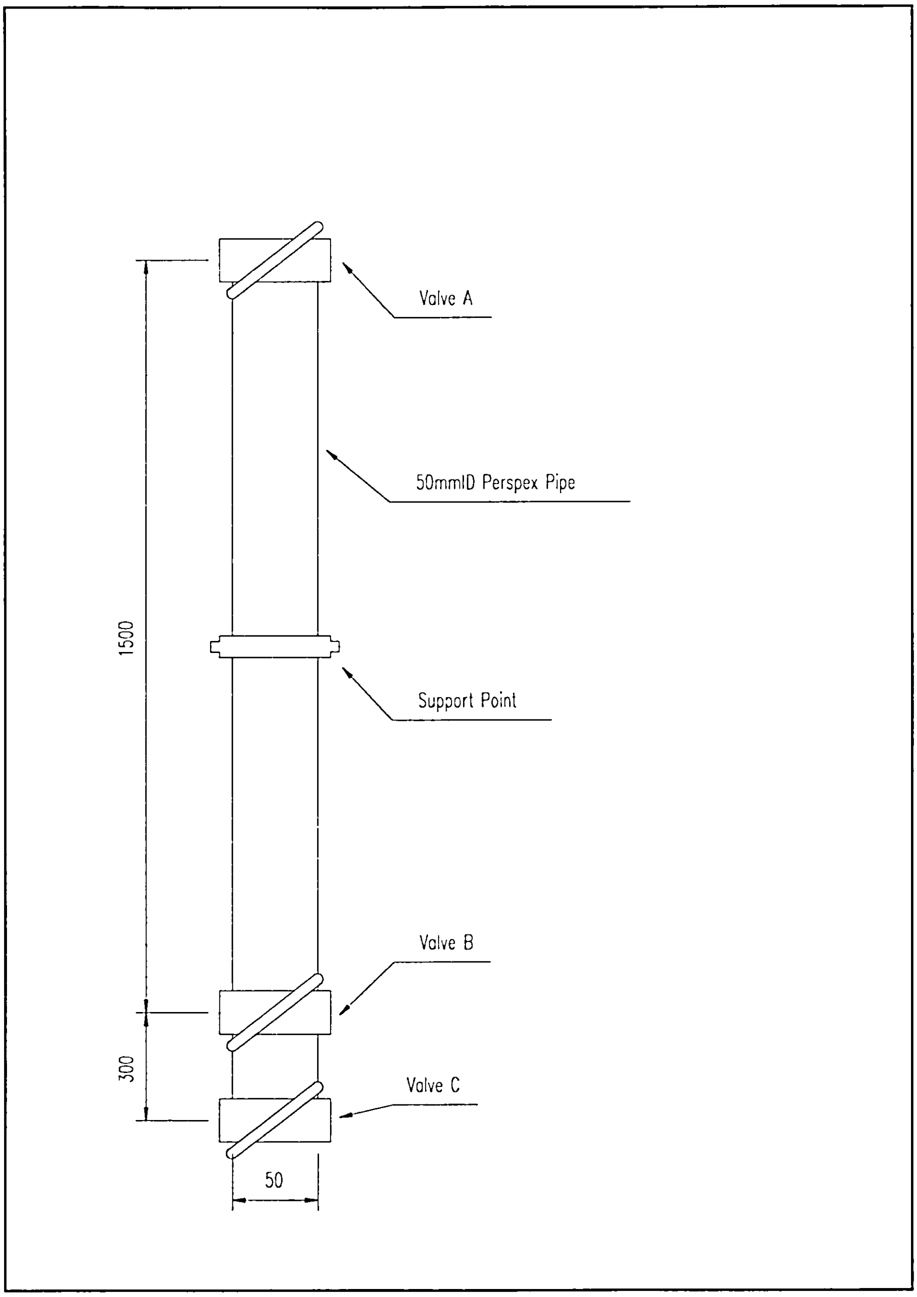

Figure C.1 : S.D.D settling velocity apparatus

C.2.5 UFT Method (Michelbach & Wöhrle, 1992a)

In this method a pre-settled sample is tested in a comparatively short column (0.7m). Typically, the test is limited to particles which have a settling velocity in excess of 0.097mm/s. Additionally, this method is principally suited for fine (suspended) particles

This methodology is promoted extensively in Germany, and wider afield (Pisano, 1995). The results from the tests being widely applied to the design of sewerage ancillary structures and treatment facilities (e.g. Michelbach & Weiss, 1995 and Weiss and Michelbach, 1995).

C.2.6 Dundee Institute of Technology[#] / Aston University Method (Wotherspoon, 1994)

Both of these establishments have carried out similar settlement velocity testing methodologies based on the method proposed by the Scottish Development Department and Heriot-Watt University (S.D.D., 1980). The apparatus consists of a settling column which pivots about its mid-point to allow mixing and determination of the velocity of any rising fraction.

The methodology, as employed by Aston University, has changed over the years, as the apparatus has been employed based on the variation is in the materials to be tested.

C.3 Methods Employed

The settling velocity methods employed as part of this study were based on the UFT method and that used previously at the University of Abertay Dundee (Wotherspoon, 1994).

C.3.1 UFT Methodology

The apparatus, shown in Figure C.2, consists on a transparent hollow cylindrical column (D_i=50mm) 700mm long which tapers into an Imhoff cone at the bottom. At the top of the column a second section of open ended cylinder, of the same internal diameter, is housed inside a small container fixed to the top of the main column. Settled samples are drawn of via a silicon tube, which is fixed to the base of the Imhoff cone, flow is controlled by a small clamp.

The column is filled with distilled water to a level 10mm above the top of the cylinder, i.e. filling 10mm of the container at the top of the column. The water temperature should be held at 20°C. The small movable cylinder is then placed in the container at the top of the column and filled with the sample to be tested. The top

[#] Now University of Abertay Dundee

of the small cylinder is sealed using a small sheet of wetted glass[$] , and then moved immediately over the open end of the settling column. At this point timing starts.

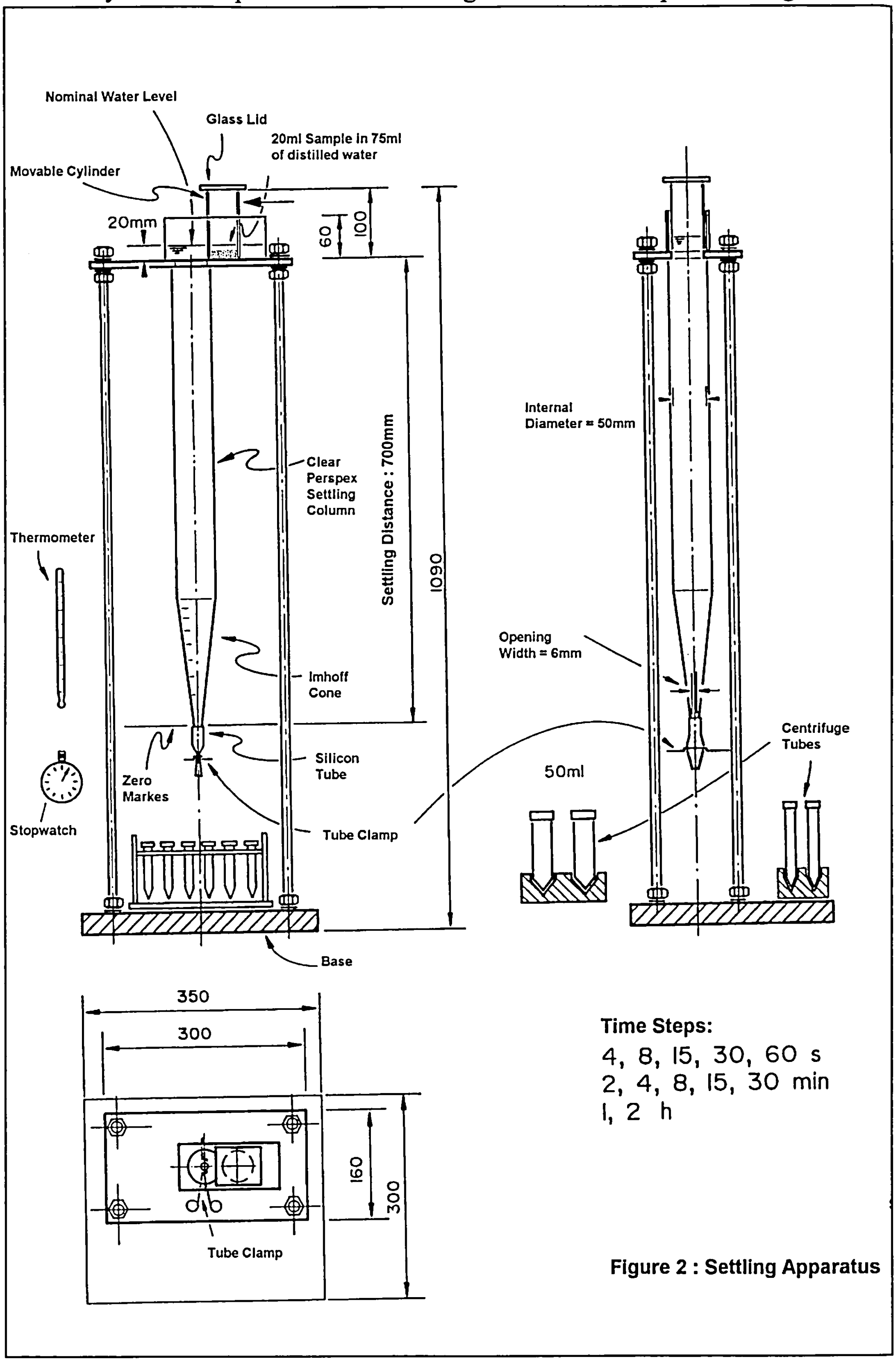

Figure C.2 : UFT settling apparatus

[$] The airtight closure of the sample container avoids the rapid mixing of the sample with the distilled water in the main column.

Once settling has been initiated samples are drawn off at intervals which increase by approximately 100% each time; 4 seconds, 8", 15", 30", 60", 2', 4', 8', 15', 30', 60' and eventually 2 hours. At the end of each time step a sample of 15ml is drawn off, however for the higher fall velocities larger sub-samples are recommended. As the testing proceeds, material may be deposited in the wall of the cone, this material should be dislodged during each time step by tapping the outside of the cone.

The settling velocity can then be estimated by dividing the fall distance (700mm) by the settling time. Using the weight of solids in each sub-sample a graph of cumulative mass settled can then be plotted against settling velocity.

The designers of the UFT column were contacted directly and design drawings and test methodologies were obtained in German language text. The text was translated by a researcher with knowledge of technical German. However, the translation did not include the pre-test process through which the samples must pass. This was not noticed until the fieldwork programme was well underway, at which point it was decided to continue with the (inadvertently) modified test procedure. The pre-test procedure consisted of separating the sampling into two fractions; that with a settling velocity in excess of 0.056mm/s, and that outside this range (which are not tested). This is done by settling the material in an Imhoff cone for 2 hours. This results in a concentrated sediment sample which forms a macro floc, which then must be reconstituted. It is the opinion of the researcher that this pre-test procedure will result in a sample which does not represent the actual settling characteristics of the material, this is confirmed by the work of Aiguier et al. (1995).

C.3.2 Dundee Institute of Technology Methodology

The apparatus used is the same as that described in section "C.2.3 Scottish Development Department Method", but the distance between valve B and Valve C is 250mm. The procedure, as applied in Dundee, is as follows;

1. With Valve A closed, the length of column between Valves A and B is filled with the sewage sample to be tested. Where the sample to be tested is a deposited sediment, or similar, a representative amount of the sample is placed in this section of column and then the compartment is filled with distilled water.
2. Valve B is then closed.
3. The section of the column between Valves B and C is then filled with distilled water.

4. Valve C is than closed.
5. The contents of the column are then mixed, by rotating the column, until the sample is evenly distributed along the section between Valves B and C.
6. The column is than positioned vertically, with Valve C at the bottom.
7. Valve B is then opened for a predetermined timed interval.
8. Some material will than have moved from the section of column between Valves A and B into that between B and C. The liquid is then removed from between valves B and C, via valve C, and the mass of settled solids determined.
9. In determining the material settled for each time step, it is assumed that any typical settled particle will move from the middle of the larger section of the column to the middle of the smaller section as the time step ends.
10. Steps 3 through to 9 are then repeated for the remainder of the sample for successively longer time steps until the required minimum settling velocity is reached.

C.4 Results

C.4.1 Sewage

A total of 13 sewage sample sets were tested for settling velocity characteristics, using the UFT methodology. The results of testing are described in Table 1

Due to logistical problems in the laboratory, settling velocity tests were frequently undertaken more than 24 hours after samples were obtained from the field. This is not ideal, but was unavoidable. Additionally, only one sample (composite) was tested for each data sets collected. The samples tested do, however, give an indication of the range of settling velocities to be expected at this site.

TABLE C.1 : Settling Velocity Results - Study Site 3 Sewage

Figure	Date	Time (GMT)	Settling Velocity (mm/s)
Figure C.3	08.03.95	11:32	1.2
Figure C.4	29.03.95	10:56	0.75
Figure C.5	26.04.95	10:17	1.25
Figure C.6	03.05.95	09:47	0.9
Figure C.7	17.05.96a	02:48	3.0
Figure C.8	13.06.95a	14:24	0.5
Figure C.9	13.06.95b	15:50	1.3
Figure C.10	20.06.95a	05:53	1.1
Figure C.11	20.06.95b	07:36	0.8
Figure C.12	17.07.95a	16:48	1.0
Figure C.13	17.07.95b	18:12	1.1
Figure C.14	26.07.95	22:03	1.05
Figure C.15	26.07.95	00:29	2.8

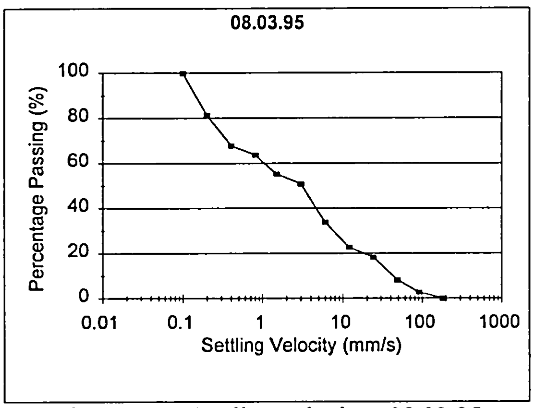

Figure C.3 : Settling velocity - 08.03.95

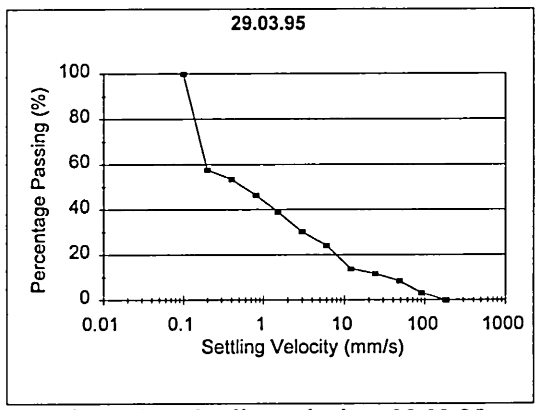

Figure C.4 : Settling velocity - 29.03.95

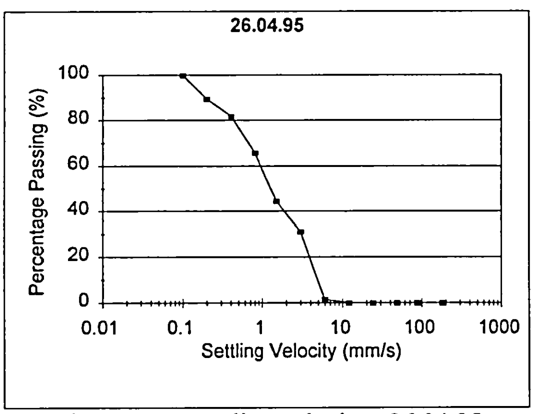

Figure C.5 : Settling velocity - 26.04.95

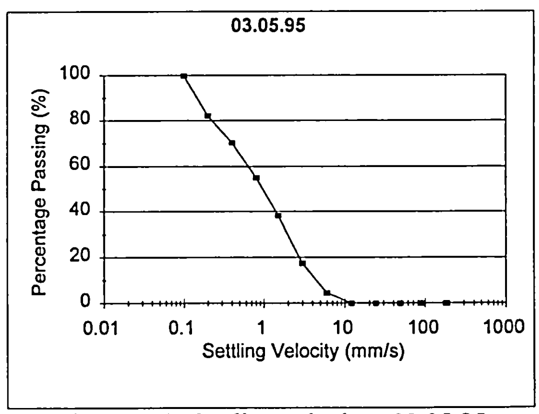

Figure C.6 : Settling velocity - 03.05.95

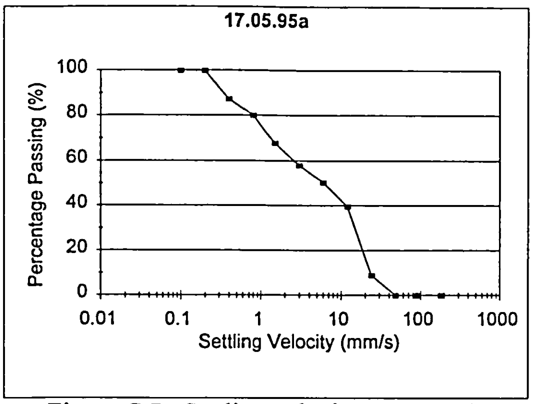

Figure C.7 : Settling velocity - 17.05.96a

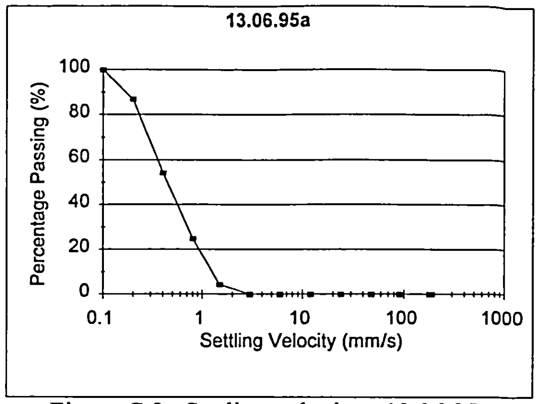

Figure C.8 : Settling velocity - 13.06.95a

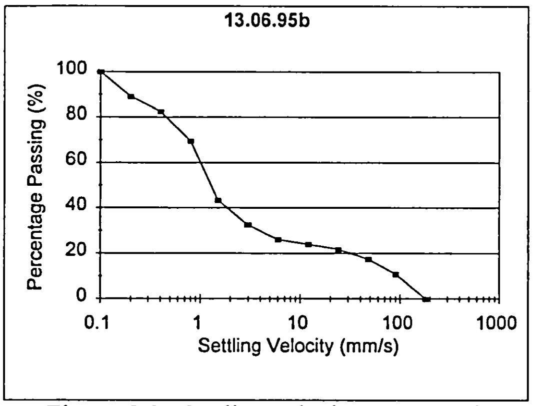

Figure C.9 : Settling velocity - 13.06.95b

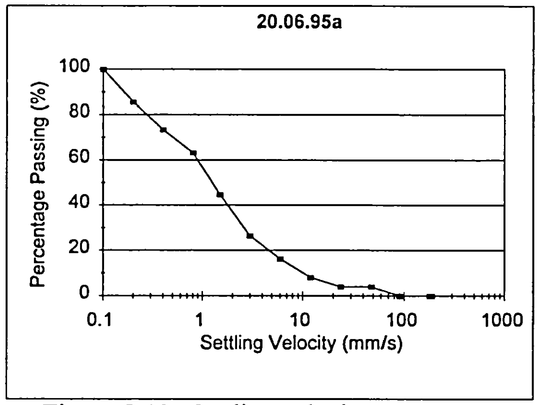

Figure C.10 : Settling velocity - 20.06.95a

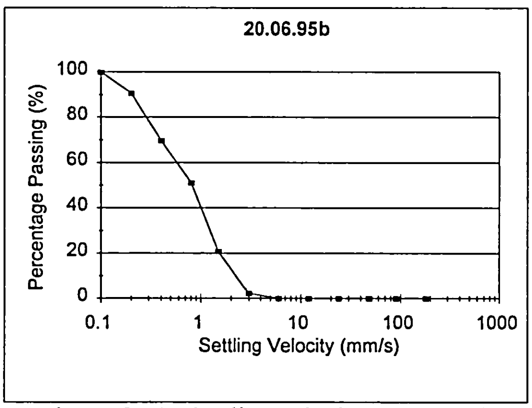

Figure C.11 : Settling velocity - 20.06.95b

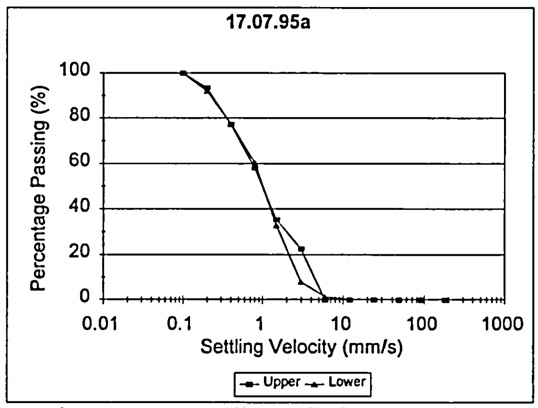

Figure C.12 : Settling velocity - 17.07.95a

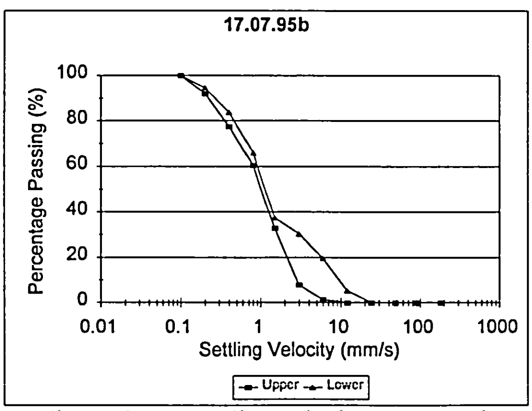

Figure C.13 : Settling velocity - 17.07.95b

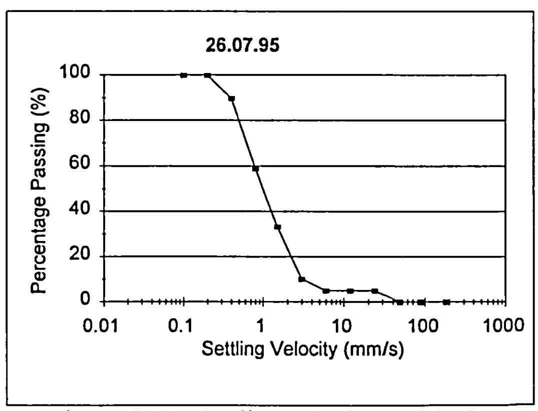

Figure C.14 : Settling velocity - 26.07.95

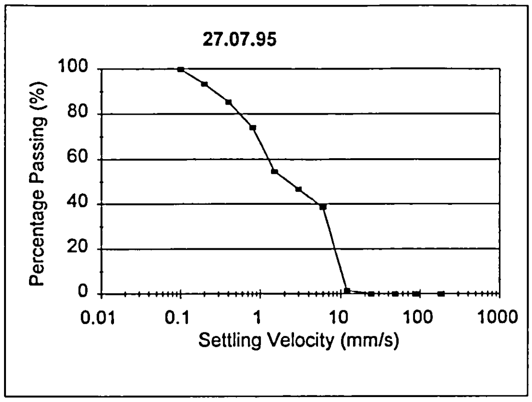

Figure C.15 : Settling velocity - 26.07.95

C4.2 Near Bed Solids

The samples of near bed solids obtained as part of the data collection at Study Site 3, were also tested for settling velocity characteristics, two methods were employed;

1. The UFT method was used on the samples of material moving at the bed obtained using small bore samples.
2. The Dundee Institute of Technology method was used on the material collocated in the invert traps.

C4.2.1 Small Bore Samples

Figures 16, 17 and 18 illustrate the settling velocity distributions for the multi-depth solids samples obtained at Study Site 3. For each of the sample sets it can be seen that the settling velocity of the material in transport at the bed is slightly higher than that moving higher in the flow column.

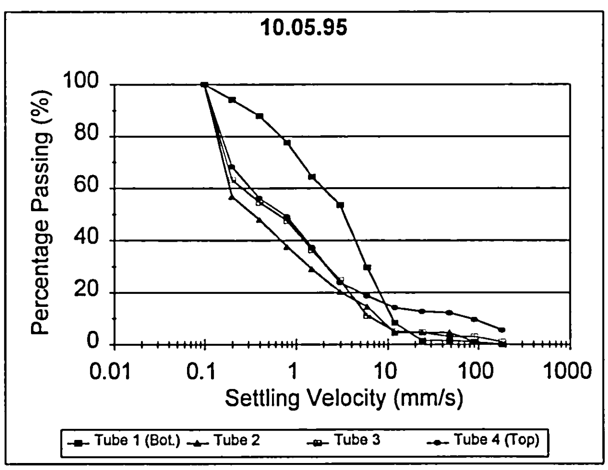

Figure C.16 : Settling velocity - 10.05.95

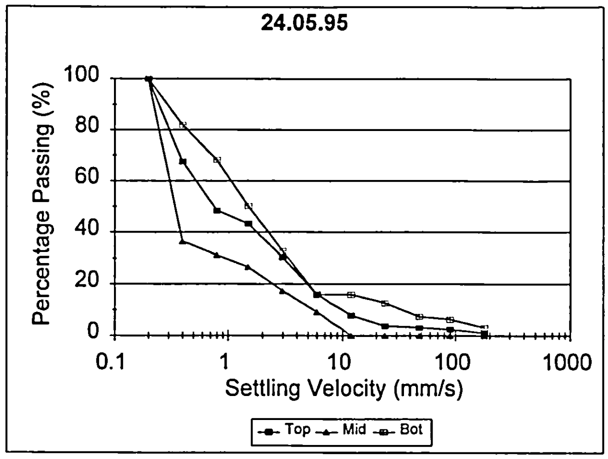

Figure C.17 : Settling velocity - 24.05.95

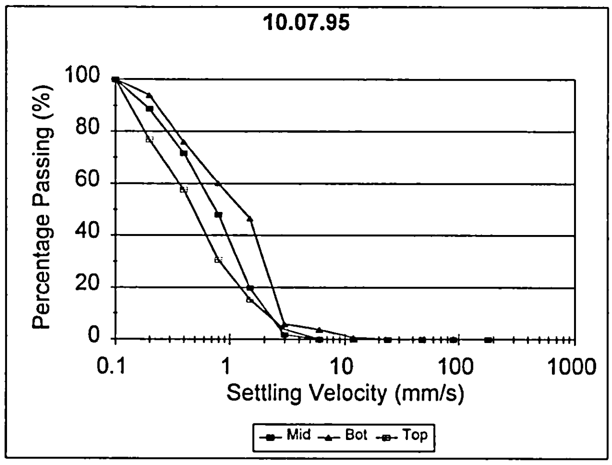

Figure C.18 : Settling velocity - 10.07.95

C4.2.2 Invert Trap Samples

The entire sample was tested together (organic + inorganic) using the Dundee Institute of Technology methodology. The methodology gave median settling velocities in the range 2.1 - 10.1 mm/s, with 5% - 32% of the solids having a settling velocity in excess of 10.5mm/s. Samples obtained when velocity conditions were low were at the lower end of this range. Settling velocity tests carried out on the material moving at the bed obtained via small bore sampling hoses had a settling velocity of 3.5 - 4.5mm/s, whilst sewage had a range of 0.75 - 3mm/s.

These results indicate that the small bore sampling procedure does not entirely represent the mass of solids in transport at the invert. Additionally the results also confirm that the settling velocity of the material in transport at the bed is greater than that of the suspended solids phase.

Study Site 1
Dens Brae Data 06.07.92
DWF 15 Minute Test   Flow Data Assumed
Test Duration (BST) : 14.35 to 14.50, 06.07.920

Samp No	Time	Suspended Solids		Flow	SS Transport Rate		Trap Fill	Cum Mass Trans.		Cum Trap Fill		Cumulative
		Total	Volatile	Flow	Total	Volatile	Rate	TSS	VSS	Total	Volatile	Flow
	(s)	(mg/l)	(mg/l)	(l/s)	(mg/s)	(mg/s)	(mg/s)	(Kg)	(Kg)	(Kg)	(Kg)	(m^3)
1	0	206	189	44.1	9085	8335	1321	0.000	0.000	0.000	0.000	0.0
2	30	243	163	45.5	11057	7417	1321	0.332	0.222	0.040	0.000	1.4
3	60	336	120	43.9	14750	5268	1321	0.774	0.381	0.079	0.001	2.7
4	90	485	146	43.9	21291	6409	1321	1.413	0.573	0.119	0.001	4.0
5	120	339	140	43	14577	6020	1321	1.850	0.753	0.159	0.001	5.3
6	150	222	124	42.6	9457	5282	1321	2.134	0.912	0.198	0.002	6.6
7	180	228	154	40.9	9325	6299	1321	2.414	1.101	0.238	0.002	7.8
8	210	241	155	39.8	9592	6169	1321	2.701	1.286	0.277	0.002	9.0
9	240	202	139	40.8	8242	5671	1321	2.949	1.456	0.317	0.003	10.2
10	270	178	139	40.8	7262	5671	1321	3.167	1.626	0.357	0.003	11.4
11	300	153	136	40.8	6242	5549	1321	3.354	1.793	0.396	0.004	12.7
12	330	154	151	40.8	6283	6161	1321	3.542	1.977	0.436	0.004	13.9
13	360	209	169	40.8	8527	6895	1321	3.798	2.184	0.476	0.004	15.1
14	390	225	158	35.5	7988	5609	1321	4.038	2.353	0.515	0.005	16.2
15	420	275	151	36.7	10092	5542	1321	4.341	2.519	0.555	0.005	17.3
16	450	243	138	35.6	8651	4913	1321	4.600	2.666	0.594	0.005	18.3
17	480	217	140	38	8246	5320	1321	4.847	2.826	0.634	0.006	19.5
18	510	192	140	43.4	8333	6076	1321	5.097	3.008	0.674	0.006	20.8
19	540	165	134	40.8	6732	5467	1321	5.299	3.172	0.713	0.006	22.0
20	570	178	150	40.8	7262	6120	1321	5.517	3.356	0.753	0.007	23.2
21	600	169	146	40.8	6895	5957	1321	5.724	3.534	0.793	0.007	24.5
22	630	160	144	40.8	6528	5875	1321	5.920	3.711	0.832	0.007	25.7
23	660	167	156	40.8	6814	6365	1321	6.124	3.902	0.872	0.008	26.9
24	690	137	131	40.8	5590	5345	1321	6.292	4.062	0.911	0.008	28.1
25	720	141	136	40.8	5753	5549	1321	6.465	4.228	0.951	0.008	29.4
26	750	137	132	40.8	5590	5386	1321	6.632	4.390	0.991	0.009	30.6
27	780	348	334	40.8	14198	13627	1321	7.058	4.799	1.030	0.009	31.8
28	810	143	138	40.8	5834	5630	1321	7.233	4.968	1.070	0.009	33.0
29	840	122	115	40.8	4978	4692	1321	7.383	5.109	1.110	0.010	34.2
30	870	140	127	40.8	5712	5182	1321	7.554	5.264	1.149	0.010	35.5
31	900	132	117	40.8	5386	4774	1321	7.716	5.407	1.189	0.010	36.7

Studt Site 1
Dens Brae Data 15.07.92
DWF 15 Minute Test
Test Duration (BST) : 14.10 to 14.25, 15.07.92

Samp No	Time (s)	Suspended Solids Total (mg/l)	Suspended Solids Volatile (mg/l)	Flow (l/s)	Depth (m)	Velocity (l/s)	SS Transport Rate Total (mg/s)	SS Transport Rate Volatile (mg/s)	Trap Fill Rate (mg/s)	Cum Mass Trans. TSS (mg)	Cum Mass Trans. VSS (mg)	Cum Trap Fill Total (mg)	Cum Trap Fill Volatile (mg)	Cumulative Flow (l)
1	0	170	167	52.0	0.193	0.80	8840	8684	725	0.000	0.000	0.000	0.000	0
2	30	173	169	49.0	0.188	0.78	8477	8281	725	0.260	0.254	0.022	0.000	1.515
3	60	189	180	49.8	0.190	0.78	9412	8964	725	0.528	0.513	0.043	0.001	2.997
4	90	216	205	46.5	0.188	0.74	10044	9533	725	0.820	0.791	0.065	0.001	4.4415
5	120	172	168	50.4	0.190	0.79	8669	8467	725	1.101	1.061	0.087	0.001	5.895
6	150	124	123	51.5	0.201	0.75	6386	6335	725	1.326	1.283	0.109	0.002	7.4235
7	180	165	164	48.0	0.203	0.69	7920	7872	725	1.541	1.496	0.130	0.002	8.916
8	210	174	171	45.5	0.204	0.65	7917	7781	725	1.779	1.731	0.152	0.002	10.3185
9	240	159	155	46.1	0.206	0.65	7330	7146	725	2.007	1.954	0.174	0.003	11.6925
10	270	137	133	47.2	0.205	0.67	6466	6278	725	2.214	2.156	0.196	0.003	13.092
11	300	169	163	48.0	0.203	0.69	8112	7824	725	2.433	2.367	0.217	0.004	14.52
12	330	144	107	46.3	0.202	0.67	6667	4954	725	2.655	2.559	0.239	0.004	15.9345
13	360	185	174	46.3	0.202	0.67	8566	8056	725	2.883	2.754	0.261	0.004	17.3235
14	390	174	159	46.5	0.198	0.69	8091	7394	725	3.133	2.986	0.283	0.005	18.7155
15	420	167	164	45.0	0.198	0.67	7515	7380	725	3.367	3.207	0.304	0.005	20.088
16	450	168	158	45.5	0.204	0.65	7644	7189	725	3.594	3.426	0.326	0.005	21.4455
17	480	158	151	46.3	0.204	0.66	7315	6991	725	3.819	3.639	0.348	0.006	22.8225
18	510	254	243	47.4	0.201	0.69	12040	11518	725	4.109	3.916	0.370	0.006	24.228
19	540	181	165	43.0	0.195	0.65	7783	7095	725	4.406	4.196	0.391	0.006	25.584
20	570	236	217	43.4	0.199	0.64	10242	9418	725	4.677	4.443	0.413	0.007	26.88
21	600	198	188	42.0	0.194	0.64	8316	7896	725	4.955	4.703	0.435	0.007	28.161
22	630	174	167	43.0	0.195	0.65	7482	7181	725	5.192	4.929	0.457	0.007	29.436
23	660	170	161	43.4	0.199	0.64	7378	6987	725	5.415	5.142	0.478	0.008	30.732
24	690	178	161	46.8	0.199	0.69	8330	7535	725	5.651	5.359	0.500	0.008	32.085
25	720	195	166	45.0	0.198	0.67	8775	7470	725	5.907	5.585	0.522	0.008	33.462
26	750	186	162	45.8	0.200	0.67	8519	7420	725	6.167	5.808	0.544	0.009	34.824
27	780	148	128	45.0	0.200	0.66	6660	5760	725	6.394	6.006	0.565	0.009	36.186
28	810	156	146	44.7	0.199	0.66	6973	6526	725	6.599	6.190	0.587	0.009	37.5315
29	840	174	115	49.5	0.201	0.72	8613	5693	725	6.833	6.373	0.609	0.010	38.9445
30	870	209	182	48.0	0.203	0.69	10032	8736	725	7.112	6.590	0.630	0.010	40.407
31	900	123	114	44.9	0.202	0.65	5523	5119	725	7.346	6.797	0.652	0.010	41.8005

Study Site 1
Dens Brae Data 21/07/92
Storm
Test Duration (BST) : 14:05 21/07/92 TO 08:00 22/07/92 Due to extreme rainfall

Samp	Time (m)	Suspended Solids Total (mg/l)	Suspended Solids Volatile (mg/l)	Rain Intensity (mm/h)	Flow (l/s)	Depth (m)	Velocity (l/s)	SS Transport Rate Total (mg/s)	SS Transport Rate Volatile (mg/s)	Trap Fill Rate (mg/s)	Cum Trans Rate TSS (Kg)	Cum Trans Rate VSS (Kg)	Cum Trap Fill Rate Total (Kg)	Cum Trap Fill Rate Volatile (Kg)	Flow (m^3)
1	2	135	134	0.67	160.2	0.325	1.30	21627	21467	65	0.000	0.000	0.000	0.000	0.000
2	4	120	120		150.5	0.328	1.21	18060	18060	65	1190.610	71.148	0.234	0.001	9.321
3	6	121	120		142.2	0.311	1.21	17206	17064	65	2248.596	134.371	0.468	0.002	18.102
4	8	55	55	1.20	130.4	0.297	1.17	7172	7172	65	2979.942	177.996	0.702	0.003	26.280
5	10	122	122	12.00	118.7	0.282	1.13	14481	14481	65	3629.544	216.972	0.936	0.004	33.753
6	12	106	105	6.00	104.4	0.269	1.05	11066	10962	65	4395.978	262.770	1.170	0.005	40.446
7	14	186	183	6.00	100.7	0.266	1.03	18730	18428	65	5289.876	315.673	1.404	0.006	46.599
8	16	318	309	4.00	90.4	0.255	0.97	28747	27934	65	6714.198	399.124	1.638	0.007	52.332
9	18	141	138		84.2	0.247	0.94	11872	11620	65	7932.780	470.319	1.872	0.008	57.570
10	20	204	181	2.40	92.6	0.256	0.99	18890	16761	65	8855.658	521.404	2.106	0.009	62.874
11	22	194	169	12.00	100.7	0.266	1.03	19536	17018	65	10008.444	582.206	2.340	0.010	68.673
12	24	187	157	12.00	107.9	0.279	1.04	20177	16940	65	11199.837	643.331	2.574	0.011	74.931
13	26	212	156	12.00	111.7	0.274	1.10	23680	17425	65	12515.568	705.189	2.808	0.012	81.519
14	28	456	352	6.00	102.1	0.273	1.01	46558	35939	65	14622.708	801.245	3.042	0.013	87.933
15	30	599	478	6.00	116.0	0.292	1.06	69484	55448	65	18103.956	965.742	3.276	0.014	94.476

Study Site 1
Dens Brae Data 27.07.92
DWF 50 Minute Test
Test Duration (BST) : 10.30 to 11.20, 27.07.92

Samp No	Time	Suspended Solids Total (mg/l)	Suspended Solids Volatile (mg/l)	Flow (l/s)	Depth (m)	Velocity (l/s)	SS Transport Rate Total (mg/s)	SS Transport Rate Volatile (mg/s)	Trap Fill Rate (mg/s)	Cumm Mass Trans TSS (Kg)	Cumm Mass Trans VSS (Kg)	Cum Trap Fill Total (Kg)	Cum Trap Fill Volatile (Kg)	Flow (m^3)
1	10.5	206	188	49.0	0.197	0.73	10094	9212	911	0.606	1105440.0	109320.000	0.000	0.000
2	10.5	229	207	44.9	0.202	0.65	10282	9294	911	1.828	1105441.1	109320.109	0.001	5.634
3	10.6	174	159	49.6	0.208	0.69	8630	7886	911	2.963	1105442.1	109320.219	0.002	11.304
4	10.6	183	166	32.0	0.188	0.51	5856	5312	911	3.832	1105442.9	109320.328	0.003	16.200
5	10.6	249	224	34.2	0.200	0.50	8516	7661	911	4.694	1105443.7	109320.437	0.004	20.172
6	10.7	209	181	35.5	0.203	0.51	7420	6426	911	5.651	1105444.6	109320.547	0.005	24.354
7	10.7	213	181	31.2	0.196	0.47	6646	5647	911	6.494	1105445.3	109320.656	0.006	28.356
8	10.7	172	150	37.9	0.207	0.53	6519	5685	911	7.284	1105446.0	109320.765	0.008	32.502
9	10.8	200	167	33.6	0.197	0.50	6720	5611	911	8.079	1105446.6	109320.875	0.009	36.792
10	10.8	102	92	42.0	0.215	0.56	4284	3864	911	8.739	1105447.2	109320.984	0.010	41.328
11	10.8	484	348	32.1	0.200	0.47	15536	11171	911	9.928	1105448.1	109321.093	0.011	45.774
12	10.9	297	157	33.9	0.202	0.49	10068	5322	911	11.464	1105449.1	109321.203	0.012	49.734
13	10.9	213	156	33.6	0.204	0.48	7157	5242	911	12.498	1105449.7	109321.312	0.013	53.784
14	10.9	179	144	33.6	0.196	0.55	6014	4838	911	13.288	1105450.3	109321.421	0.014	57.816
15	11.0	227	171	34.8	0.206	0.49	7900	5951	911	14.123	1105451.0	109321.530	0.015	61.920
16	11.0	238	154	35.0	0.201	0.51	8330	5390	911	15.097	1105451.7	109321.640	0.016	66.108
17	11.0	203	199	34.5	0.202	0.50	7004	6866	911	16.017	1105452.4	109321.749	0.017	70.278
18	11.1	148	100	30.7	0.200	0.45	4544	3070	911	16.710	1105453.0	109321.858	0.018	74.190
19	11.1	205	164	36.9	0.195	0.56	7565	6052	911	17.436	1105453.5	109321.968	0.019	78.246
20	11.1	198	168	34.4	0.204	0.49	6811	5779	911	18.299	1105454.3	109322.077	0.021	82.524
21	11.2	201	180	34.5	0.196	0.52	6935	6210	911	19.123	1105455.0	109322.186	0.022	86.658
22	11.2	182	140	35.5	0.197	0.53	6461	4970	911	19.927	1105455.6	109322.296	0.023	90.858
23	11.2	207	177	36.6	0.196	0.55	7576	6478	911	20.769	1105456.3	109322.405	0.024	95.184
24	11.3	193	166	37.7	0.193	0.58	7276	6258	911	21.661	1105457.1	109322.514	0.025	99.642
25	11.3	196	170	35.3	0.199	0.52	6919	6001	911	22.512	1105457.8	109322.624	0.026	104.022
26	11.3	182	151	35.3	0.196	0.53	6425	5330	911	23.313	1105458.5	109322.733	0.027	108.258

Study Site 1
Dens Brae Data 29.07.92
DWF 24 Hour Test

		Suspended Solids					SS Transport Rate		Trap Fill	Cum Mass Trans		Cum Trap Fill		
sample	Time (H)	Total (mg/l)	Volatile (mg/l)	Flow (l/s)	Depth (m)	Velocity (m/s)	Total (mg/s)	Volatile (mg/s)	Rate (mg/s)	TSS (Kg)	VSS (Kg)	Total (Kg)	Volatile (Kg)	Flow (l)
1	0	153	140	30.2	0.201	0.44	4621	4228	27	0.0	0.0	0.000	0.000	0.000
2	1	128	116	41.4	0.204	0.59	5299	4802	27	17.9	16.3	0.097	0.016	128.880
3	2	186	176	36.3	0.195	0.55	6752	6389	27	39.5	36.4	0.194	0.031	268.740
4	3	143	128	32.6	0.196	0.49	4662	4173	27	60.1	55.4	0.292	0.047	392.760
5	4	197	186	42.0	0.206	0.59	8274	7812	27	83.4	77.0	0.389	0.063	527.040
6	5	125	116	45.0	0.221	0.58	5625	5220	27	108.4	100.4	0.486	0.078	683.640
7	6	182	152	37.2	0.214	0.50	6770	5654	27	130.7	120.0	0.583	0.094	831.600
8	7	164	135	45.8	0.221	0.59	7511	6183	27	156.4	141.3	0.680	0.110	981.000
9	8	141	122	42.3	0.211	0.58	5964	5161	27	180.7	161.7	0.778	0.125	1139.580
10	9	108	99	37.4	0.205	0.53	4039	3703	27	198.7	177.7	0.875	0.141	1283.040
11	10	64	64	33.1	0.192	0.51	2118	2118	27	209.8	188.2	0.972	0.156	1409.940
12	11	45	44	28.5	0.181	0.177	1283	1254	27	215.9	194.2	1.069	0.172	1520.820
13	12	34	28	27.4	0.170	0.50	932	767	27	219.9	197.9	1.166	0.188	1621.440
14	13	19	25	22.6	0.164	0.43	429	565	27	222.3	200.3	1.264	0.203	1711.440
15	14	19	18	21.0	0.159	0.42	399	378	27	223.8	202.0	1.361	0.219	1789.920
16	15	16	19	20.8	0.161	0.41	333	395	27	225.1	203.4	1.458	0.235	1865.160
17	16	28	28	23.4	0.172	0.42	655	655	27	226.9	205.3	1.555	0.250	1944.720
18	17	55	48	29.4	0.179	0.50	1617	1411	27	231.0	209.0	1.652	0.266	2039.760
19	18	170	139	41.7	0.211	0.57	7089	5796	27	246.7	222.0	1.750	0.282	2167.740
20	19	128	110	66.5	0.240	0.77	5635	4786	27	269.6	241.0	1.847	0.297	2362.500
21	20	337	257	65.2	0.244	0.74	21972	16756	27	319.3	279.8	1.944	0.313	2599.560
22	21	233	190	58.1	0.241	0.67	13537	11039	27	383.2	329.8	2.041	0.329	2821.500
23	22	220	176	50.9	0.225	0.64	11198	8958	27	427.7	365.8	2.138	0.344	3017.700
24	23	169	132	50.4	0.213	0.68	8518	6653	27	463.2	393.9	2.236	0.360	3200.040

Study Site 1
Dens Brae Data 09.09.92
DWF 24 Hour Test
Test Duration (BST) : 14.10, 08.09.92 to 14.00, 09.09.92

		Suspended Solids					SS Transport Rate		Trap Fill	Cum Trans Rate		Cum Trap Fill Rate		
Samp	Time (H)	Total (mg/l)	Volatile (mg/l)	Flow (l/s)	Depth (m)	Velocity (m/s)	Total (mg/s)	Volatile (mg/s)	Rate (mg/s)	TSS (Kg)	VSS (Kg)	Total (Kg)	Volatile (Kg)	Flow (m^3)
1	14.2	173	156	73.0	0.256	0.78	12629	11388	22	0.0	0.0	0.000	0.000	0.000
2	15.2	96	93	69.2	0.256	0.74	6643	6436	22	34.7	32.1	0.079	0.011	255.960
3	16.2	50	49	65.4	0.259	0.69	3270	3205	22	52.5	49.4	0.158	0.022	498.240
4	17.2	182	151	68.2	0.265	0.70	12412	10298	22	80.8	73.7	0.238	0.032	738.720
5	18.2	210	147	69.2	0.268	0.70	14532	10172	22	129.3	110.6	0.317	0.043	986.040
6	19.2	187	167	81.9	0.299	0.73	15315	13677	22	183.0	153.5	0.396	0.054	1258.020
7	20.2	192	143	80.8	0.276	0.79	15514	11554	22	238.5	198.9	0.475	0.065	1550.880
8	21.2	168	118	70.8	0.264	0.73	11894	8354	22	287.8	234.8	0.554	0.076	1823.760
9	22.2	114	101	67.3	0.256	0.72	7672	6797	22	323.0	262.0	0.634	0.086	2072.340
10	23.2	133	114	64.7	0.243	0.74	8605	7376	22	352.3	287.6	0.713	0.097	2309.940
11	24.2	421	402	55.5	0.238	0.65	23366	22311	22	409.9	341.0	0.792	0.108	2526.300
12	25.2	79	67	54.2	0.223	0.69	4282	3631	22	459.6	387.7	0.871	0.119	2723.760
13	26.2	38	36	48.8	0.215	0.65	1854	1757	22	470.7	397.4	0.950	0.130	2909.160
14	27.2	35	35	50.7	0.214	0.68	1775	1775	22	477.2	403.7	1.030	0.140	3088.260
15	28.2	42	30	50.0	0.209	0.69	2100	1500	22	484.2	409.6	1.109	0.151	3269.520
16	29.2	32	21	47.1	0.212	0.64	1507	989	22	490.7	414.1	1.188	0.162	3444.300
17	30.2	56	56	50.1	0.217	0.66	2806	2806	22	498.5	420.9	1.267	0.173	3619.260
18	31.2	222	188	62.0	0.237	0.73	13764	11656	22	528.3	447.0	1.346	0.184	3821.040
19	32.2	246	218	63.8	0.270	0.64	15695	13908	22	581.3	493.0	1.426	0.194	4047.480
20	33.2	68	65	63.6	0.273	0.63	4325	4134	22	617.3	525.5	1.505	0.205	4276.800
21	34.2	208	188	60.9	0.270	0.61	12667	11449	22	647.9	553.5	1.584	0.216	4500.900
22	35.2	223	199	63.1	0.268	0.64	14071	12557	22	696.1	596.7	1.663	0.227	4724.100
23	36.2	235	210	64.4	0.265	0.66	15134	13524	22	748.6	643.7	1.742	0.238	4953.600
24	37.2	192	180	50.0	0.275	0.66	9600	9000	22	793.1	684.2	1.822	0.248	5159.520

Study Site 2 : Sewage & Flow Data Summary

29.04.93, 48min DWF Sample (13:06 - 13:54)

Bottom Sampling Tube

H	M	Dec T	Depth (m)	Velocity (m/s)	Discharge (m^3/s)	TSS (mg/l)	VSS (mg/l)	Ammonia (mg/l)	BOD (mg/l)	COD (mg/l)	TSS Trans (mg/s)	VSS Trans (mg/s)	Cumm Flow (M^3)	Cumm TSS (Kg)	Cumm VSS (kg)
13	8	13.13	0.359	0.380	0.087	186	173				16246.1	15110.7	10.47	1.81	1.69
13	10	13.17	0.357	0.383	0.087	159	150	22.96	249	600	13862.2	13077.5	21.32	3.42	3.21
13	12	13.20	0.358	0.410	0.094	139	130				13024.6	12181.3	32.37	5.07	4.76
13	14	13.23	0.354	0.403	0.090	159	150	21.19	148	495	14375.9	13562.1	43.40	6.65	6.24
13	16	13.27	0.354	0.417	0.093	127	118				11866.6	11025.7	54.63	8.08	7.57
13	18	13.30	0.354	0.417	0.094	128	119	20.36	142	460	11992.1	11148.9	65.62	9.85	9.23
13	20	13.33	0.351	0.403	0.089	194	183				17356.0	16371.9	76.15	11.47	10.75
13	22	13.37	0.354	0.383	0.086	114	107	18.05	142	445	9811.3	9208.9	86.79	12.66	11.87
13	24	13.40	0.352	0.410	0.091	109	104				9944.6	9488.4	97.50	13.79	12.92
13	26	13.43	0.353	0.390	0.087	102	91	21.19	165	460	8904.4	7944.1	107.99	15.06	14.08
13	28	13.47	0.350	0.397	0.088	141	130				12349.2	11385.8	118.73	16.41	15.33
13	30	13.50	0.350	0.413	0.091	110	104	22.06	261	480	10043.2	9495.4	129.56	17.83	16.67
13	32	13.53	0.353	0.400	0.089	152	142				13570.2	12677.4	140.37	19.39	18.14
13	34	13.57	0.351	0.410	0.091	137	131	18.79	142	480	12443.3	11898.3	151.27	20.88	19.57
13	36	13.60	0.351	0.410	0.091	137	131				12443.3	11898.3	162.11	22.17	20.78
13	38	13.63	0.350	0.407	0.090	101	92	18.79	131	410	9070.9	8262.6	172.79	23.41	21.93
13	40	13.67	0.350	0.400	0.088	130	124				11468.0	10938.7	183.35	24.74	23.19
13	42	13.70	0.349	0.400	0.088	123	114	21.19	102	455	10801.8	10011.4	193.89	26.02	24.39
13	44	13.73	0.349	0.400	0.088	120	114				10538.3	10011.4	204.22	27.21	25.50
13	46	13.77	0.346	0.390	0.084	110	101	18.79	142	520	9290.5	8530.4	214.47	28.23	26.46
13	48	13.80	0.347	0.397	0.086	89	87				7681.2	7508.6	224.53	29.06	27.27
13	50	13.83	0.347	0.373	0.081	77	73	21.19	125	490	6264.2	5938.8	234.49	29.67	27.85
13	52	13.87	0.346	0.390	0.085	44	44				3722.7	3722.7	244.64	30.11	28.30

Top Sampling Tube

H	M	Dec T	Depth (m)	Velocity (m/s)	Discharge (m^3/s)	TSS (mg/l)	VSS (mg/l)	Ammonia (mg/l)	BOD (mg/l)	COD (mg/l)	TSS Trans (mg/s)	VSS Trans (mg/s)	Cumm Flow (M^3)	Cumm TSS (Kg)	Cumm VSS (kg)
13	8	13.13	0.359	0.380	0.087	117	109				10219.3	9520.6	10.47	1.37	1.28
13	10	13.17	0.357	0.383	0.087	145	135	21.19	193	580	12641.6	11769.8	21.32	2.88	2.70
13	12	13.20	0.358	0.410	0.094	133	128				12462.4	11993.9	32.37	4.18	3.79
13	14	13.23	0.354	2.000	0.090	103	68	19.56	125	440	9312.7	6148.2	43.40	5.31	4.76
13	16	13.27	0.354	0.417	0.093	102	109				9530.7	10184.7	54.63	6.53	5.99
13	18	13.30	0.354	0.417	0.094	115	109	18.05	125	510	10774.1	10212.0	65.62	7.80	7.20
13	20	13.33	0.351	0.403	0.089	115	112				10288.3	10019.9	76.15	9.34	8.71
13	22	13.37	0.354	0.383	0.086	179	174	20.36	131	445	15405.5	14975.2	86.79	10.84	10.18
13	24	13.40	0.352	0.410	0.091	102	102				9306.0	9306.0	97.50	11.92	11.24
13	26	13.43	0.353	0.390	0.087	100	96	19.56	136	495	8729.8	8380.6	107.99	13.02	12.31
13	28	13.47	0.350	0.397	0.088	109	108				9546.6	9459.0	118.73	14.13	13.40
13	30	13.50	0.350	0.413	0.091	99	95	18.79	142	495	9038.9	8673.7	129.56	15.48	14.69
13	32	13.53	0.353	0.400	0.089	150	143				13391.7	12766.7	140.37	16.87	16.03
13	34	13.57	0.351	0.410	0.091	107	105	18.05	119	455	9718.5	9536.8	151.27	17.95	17.10
13	36	13.60	0.351	0.410	0.091	91	92				8265.3	8356.1	162.11	18.95	18.07
13	38	13.63	0.350	0.407	0.090	93	88	16.66	91	460	8352.4	7903.4	172.79	20.03	19.11
13	40	13.67	0.350	0.400	0.088	109	106				9615.5	9350.8	183.35	21.18	20.23
13	42	13.70	0.349	0.400	0.088			16.66	108	478			193.89	22.33	21.28
13	44	13.73	0.349	0.400	0.088	109	100				9572.3	8781.9	204.22	23.43	22.29
13	46	13.77	0.346	0.390	0.084	104	95	16.66	125	495	8783.8	8023.6	214.47	24.36	23.17
13	48	13.80	0.347	0.397	0.086	79	76				6818.1	6559.2	224.53	25.19	23.95
13	50	13.83	0.347	0.373	0.081	85	80	19.56	108	570	6915.0	6508.3	234.49	26.01	24.71
13	52	13.87	0.346	0.390	0.085	80	73				6768.5	6176.2	244.64	26.82	25.46

Study Site 2 : Sewage and Flow Data Summary

13.05.93, 48min DWF Sample (05:41 - 06:29)

Bottom Sampling Tube

H	M	Dec T	Depth (m)	Velocity (m/s)	Discharge (m^3/s)	TSS (mg/l)	VSS (mg/l)	Ammonia (mg/l)	BOD (mg/l)	COD (mg/l)	Cumm Flow (M^3)	TSS Trans (mg/s)	VSS Trans (mg/s)	Cumm TSS (Kg)	Cumm VSS (kg)
5	41	5.683	0.307	0.300	0.054	92	94			180	6.60	4964.2	5072.1	0.50	0.52
5	43	5.717	0.308	0.310	0.056	59	64			160	13.08	3306.2	3586.4	0.87	0.93
5	45	5.750	0.306	0.290	0.052	55	61			210	19.55	2854.4	3165.8	1.35	1.45
5	47	5.783	0.308	0.310	0.056	95	100			200	26.38	5323.5	5603.7	1.90	2.02
5	49	5.817	0.308	0.320	0.058	65	68			455	33.13	3759.9	3933.4	2.33	2.48
5	51	5.850	0.309	0.300	0.055	64	68			440	39.92	3488.0	3706.0	4.27	4.35
5	53	5.883	0.311	0.320	0.059	506	484			310	46.87	29709.8	28418.1	7.14	7.10
5	55	5.917	0.312	0.310	0.057	318	305			510	53.73	18177.7	17434.6	8.50	8.41
5	57	5.950	0.312	0.310	0.057	80	79			255	60.83	4573.0	4515.8	9.09	9.01
5	59	5.983	0.313	0.330	0.061	86	89			295	68.19	5259.1	5442.5	9.78	9.71
6	1	6.017	0.314	0.330	0.061	102	102			430	75.60	6268.3	6268.3	10.65	10.59
6	3	6.050	0.316	0.330	0.062	132	135			340	83.06	8191.9	8378.1	11.89	11.60
6	5	6.083	0.317	0.330	0.062	201				355	90.56	12535.1		13.09	12.67
6	7	6.117	0.318	0.330	0.063	118	143			385	98.47	7394.9	8961.6	14.02	13.80
6	9	6.150	0.320	0.360	0.069					395	106.81			15.25	14.84
6	11	6.183	0.323	0.360	0.070	147	124			440	115.26	10295.7	8684.8	16.81	15.83
6	13	6.217	0.325	0.360	0.071	223	111			750	124.06	15769.0	7849.2	21.18	19.58
6	15	6.250	0.329	0.380	0.076	770	740			580	133.11	58577.7	56295.4	25.47	23.56
6	17	6.283	0.331	0.370	0.075	177	140			445	142.13	13235.2	10468.5	27.42	25.06
6	19	6.317	0.333	0.370	0.075	257	194			595	150.89	19398.5	14643.2	29.58	26.71
6	21	6.350	0.319	0.370	0.071	234	181			560	160.17	16522.1	12779.9	31.57	28.22
6	23	6.383	0.339	0.400	0.084	197	145			495	170.30	16529.9	12166.7	33.53	29.65
6	25	6.417	0.342	0.400	0.085	189	138			950	180.97	16078.8	11740.0	37.62	29.65
6	27	6.450	0.345	0.430	0.093	578	411				192.10	53588.3	38105.2	44.05	32.58

Top Sampling Tube

H	M	Dec T	Depth (m)	Velocity (m/s)	Discharge (m^3/s)	TSS (mg/l)	VSS (mg/l)	Ammonia (mg/l)	BOD (mg/l)	COD (mg/l)	Cumm Flow (M^3)	TSS Trans (mg/s)	VSS Trans (mg/s)	Cumm TSS (Kg)	Cumm VSS (kg)
5	41	5.683	0.307	0.300	0.054	68	72			190	6.60	3669.2	3885.0	0.42	0.44
5	43	5.717	0.308	0.310	0.056	59	62			155	13.08	3306.2	3474.3	0.75	0.80
5	45	5.750	0.306	0.290	0.052	42	47			175	19.55	2179.7	2439.2	1.01	1.10
5	47	5.783	0.308	0.310	0.056	39	47			180	26.38	2185.4	2633.7	1.31	1.44
5	49	5.817	0.308	0.320	0.058	49	52			240	33.13	2834.4	3007.9	1.62	1.76
5	51	5.850	0.309	0.300	0.055	42	43			165	39.92	2289.0	2343.5	2.03	2.19
5	53	5.883	0.311	0.320	0.059	81	83			190	46.87	4755.9	4873.3	2.61	2.79
5	55	5.917	0.312	0.310	0.057	86	91			245	53.73	4916.0	5201.8	3.09	3.31
5	57	5.950	0.312	0.310	0.057	53	60			255	60.83	3029.6	3429.8	3.50	3.76
5	59	5.983	0.313	0.330	0.061	63	68			185	68.19	3852.6	4158.3	3.98	4.28
6	1	6.017	0.314	0.330	0.061	67	72			240	75.60	4117.4	4424.7	4.55	4.89
6	3	6.050	0.316	0.330	0.062	87	94			240	83.06	5399.2	5833.6	5.22	5.60
6	5	6.083	0.317	0.330	0.062	93	95			245	90.56	5799.8	5924.6	6.05	6.43
6	7	6.117	0.318	0.330	0.063	127	128			345	98.47	7958.9	8021.6	7.00	7.40
6	9	6.150	0.320	0.360	0.069	115	115			295	106.81	7938.8	7938.8	8.04	8.44
6	11	6.183	0.323	0.360	0.070	134	135			295	115.26	9385.2	9455.2	9.33	9.72
6	13	6.217	0.325	0.360	0.071	170	169			240	124.06	12021.2	11950.5	10.66	11.05
6	15	6.250	0.329	0.380	0.076	133	133			265	133.11	10118.0	10118.0	11.80	12.14
6	17	6.283	0.331	0.370	0.075	119	107			245	142.13	8898.3	8000.9	12.94	13.14
6	19	6.317	0.333	0.370	0.075	133	116			280	150.89	10038.9	8755.7	14.19	14.26
6	21	6.350	0.319	0.370	0.071	153	138			345	160.17	10802.9	9743.8	15.57	15.47
6	23	6.383	0.339	0.400	0.084	144	124			325	170.30	12082.8	10404.6	17.19	16.87
6	25	6.417	0.342	0.400	0.085	176	153			320	180.97	14972.8	13016.1	19.13	16.87
6	27	6.450	0.345	0.430	0.093	187	158			395	192.10	17337.4	14648.7	21.21	18.53

Study Site 2 : Sewage & Flow Data Summary

19.05.93, 72min DWF Sample (06:53 - 08:05)

Bottom Sampling Tube

H	M	Dec T	Depth (m)	Velocity (m/s)	Discharge (m^3/s)	TSS (mg/l)	VSS (mg/l)	Ammonia (mg/l)	BOD (mg/l)	COD (mg/l)	Cumm Flow (M^3)	TSS Trans (mg/s)	VSS Trans (mg/s)	Cumm TSS (Kg)	Cumm VSS (kg)
6	53	6.88	0.341	0.385	0.082	192	211	27.4			15.72	15649.6	17198.2	2.54	2.55
6	56	6.93	0.341	0.440	0.093	131	114	31.0		400	31.38	12202.9	10619.3	3.96	3.89
7	59	6.98	0.342	0.380	0.081	142	141	31.0			45.54	11476.3	11395.5	5.46	5.35
7	2	7.03	0.342	0.360	0.077	175	170	31.0		400	59.15	13399.0	13016.1	6.81	6.42
7	5	7.08	0.343	0.350	0.075	122	66	29.8			73.59	9102.9	4924.5	8.05	7.39
7	8	7.13	0.344	0.400	0.086	136	135	31.0		440	88.67	11676.1	11590.2	9.43	8.77
7	11	7.18	0.345	0.380	0.082	139	139	29.8			103.05	11362.1	11362.1	10.80	10.13
7	14	7.23	0.346	0.360	0.078	147	146	29.8		440	118.23	11462.1	11384.2	12.24	11.55
7	17	7.28	0.348	0.415	0.091	137	133	35.1			134.69	12426.3	12063.5	13.75	13.02
7	20	7.33	0.349	0.420	0.092	138	135	35.1		370	150.65	12725.0	12448.4	16.45	15.21
7	23	7.38	0.351	0.385	0.085	369	277				166.79	31400.2	23571.4	19.53	17.68
7	26	7.43	0.354	0.420	0.094	205	182	33.7		515	184.62	19330.8	17161.9	21.61	20.03
7	29	7.48	0.355	0.460	0.104	145	214	28.6			201.48	15052.1	22214.8	23.22	21.98
7	32	7.53	0.355	0.370	0.083	140	132	29.8		400	216.24	11681.7	11014.1	25.14	23.76
7	35	7.58	0.354	0.360	0.081	251	231	29.8			231.99	20242.1	18629.2	27.42	25.85
7	38	7.63	0.354	0.420	0.094	183	166	31.0		550	248.95	17256.2	15653.2	29.48	27.68
7	41	7.68	0.357	0.415	0.094	182	159	31.0			266.27	17143.5	14977.0	31.85	29.79
7	44	7.73	0.358	0.430	0.098	228	205	32.3		430	284.60	22404.6	20144.5	34.59	32.14
7	47	7.78	0.359	0.460	0.105	220	181	32.3			301.34	23178.9	19069.9	37.14	34.19
7	50	7.83	0.360	0.350	0.081	238	185	29.8		410	318.05	19204.2	14927.7	39.74	36.25
7	53	7.88	0.360	0.455	0.105	229	186	32.3			334.75	24021.4	19510.9	42.19	38.26
7	56	7.93	0.360	0.350	0.081	211	174	31.0		460	351.02	17025.6	14040.1	44.43	40.08
8	59	7.98	0.360	0.435	0.100	201	163	28.6			368.95	20116.9	16313.7	47.74	40.08
8	2	8.03	0.360	0.430	0.099	354	220	24.2		690	386.79	35093.2	21809.4	51.95	42.37

Top Sampling Tube

H	M	Dec T	Depth (m)	Velocity (m/s)	Discharge (m^3/s)	TSS (mg/l)	VSS (mg/l)	Ammonia (mg/l)	BOD (mg/l)	COD (mg/l)	Cumm Flow (M^3)	TSS Trans (mg/s)	VSS Trans (mg/s)	Cumm TSS (Kg)	Cumm VSS (kg)
6	53	6.88	0.341	0.385	0.082	159	148	24.2			15.72	12959.8	12063.2	2.39	2.29
6	56	6.93	0.341	0.440	0.093	145	143	25.3		425	31.38	13507.1	13320.7	3.97	3.83
7	59	6.98	0.342	0.380	0.081	158	152	25.3			45.54	12769.4	12284.5	5.42	5.24
7	2	7.03	0.342	0.360	0.077	148	148	25.3		410	59.15	11331.7	11331.7	7.25	7.08
7	5	7.08	0.343	0.350	0.075	257	257	24.2			73.59	19175.8	19175.8	9.21	9.02
7	8	7.13	0.344	0.400	0.086	150	146	23.3		405	88.67	12878.0	12534.6	10.68	10.46
7	11	7.18	0.345	0.380	0.082	142	140	24.2			103.05	11607.3	11443.9	11.99	11.76
7	14	7.23	0.346	0.360	0.078	131	131	24.2		450	118.23	10214.5	10214.5	13.15	12.93
7	17	7.28	0.348	0.415	0.091	99	101	27.4			134.69	8979.6	9161.0	14.38	14.17
7	20	7.33	0.349	0.420	0.092	124	124	24.2		525	150.65	11434.1	11434.1	16.13	15.87
7	23	7.38	0.351	0.385	0.085	205	196	26.3			166.79	17444.6	16678.7	18.32	17.92
7	26	7.43	0.354	0.420	0.094	202	185	26.3		680	184.62	19047.9	17444.8	20.56	20.00
7	29	7.48	0.355	0.460	0.104	176	165	24.2			201.48	18270.1	17128.2	22.63	21.93
7	32	7.53	0.355	0.370	0.083	192	179	23.3		490	216.24	16020.6	14935.8	24.41	23.62
7	35	7.58	0.354	0.360	0.081	169	164	24.2			231.99	13629.2	13225.9	26.12	25.27
7	38	7.63	0.354	0.420	0.094	157	151	22.3		510	248.95	14804.5	14238.8	28.03	26.82
7	41	7.68	0.357	0.415	0.094	181	122	23.3			266.27	17049.3	11491.8	29.76	28.20
7	44	7.73	0.358	0.430	0.098	118	117	24.2		510	284.60	11595.4	11497.1	31.66	30.07
7	47	7.78	0.359	0.460	0.105	194	190	22.3			301.34	20439.6	20018.1	34.52	32.68
7	50	7.83	0.360	0.350	0.081	319	278	23.3		580	318.05	25740.1	22431.8	37.64	35.27
7	53	7.88	0.360	0.455	0.105	240	186	24.2			334.75	25175.3	19510.9	40.30	37.35
7	56	7.93	0.360	0.350	0.081	239	189	23.3		550	351.02	19284.9	15250.4	42.68	39.26
8	59	7.98	0.360	0.435	0.100	199	162	22.3			368.95	19916.8	16213.6	46.13	39.26
8	2	8.03	0.360	0.430	0.099	378	245	19.7		690	386.79	37472.5	24287.7	50.62	41.69

Study Site 2 : Sewage & Flow Data Summary

25.05.93, 48min DWF Sample

Bottom Sampling Tube

H	M	Dec T	Depth (m)	Velocity (m/s)	Discharge (m^3/s)	TSS (mg/l)	VSS (mg/l)	Ammonia (mg/l)	BOD (mg/l)	COD (mg/l)	TSS Trans (mg/s)	VSS Trans (mg/s)	Cumm Flow (M^3)	Cumm TSS (Kg)	Cumm VSS (kg)
13	51	13.850	0.321	0.400	0.077	161	154				12409.0	11869.5	9.36	1.09	1.04
13	53	13.883	0.321	0.410	0.079	72	68	32	207	730	5688.1	5372.1	18.46	2.31	2.18
13	55	13.917	0.319	0.380	0.073	196	184				14213.0	13342.8	27.84	4.02	3.83
13	57	13.950	0.319	0.440	0.084	169	167	30	348	620	14190.1	14022.2	37.90	5.73	5.45
13	59	13.983	0.318	0.440	0.084	171	154				14288.4	12867.9	47.92	7.45	7.01
14	1	14.017	0.318	0.440	0.084	171	158	32	416	660	14288.4	13202.2	57.59	9.04	8.50
14	3	14.050	0.317	0.410	0.077	158	151				12242.2	11699.8	66.95	10.50	9.89
14	5	14.083	0.315	0.420	0.079	155	145	30	173	590	12182.9	11396.9	76.47	12.06	11.38
14	7	14.117	0.314	0.430	0.080	172	169				13773.1	13532.9	86.19	13.70	12.94
14	9	14.150	0.314	0.440	0.082	165	152	32	178	425	13519.8	12454.6	95.78	15.22	14.31
14	11	14.183	0.313	0.420	0.078	154	134				11985.7	10429.2	105.25	16.66	15.59
14	13	14.217	0.314	0.430	0.080	149	135	32	399	425	11931.3	10810.3	114.84	18.00	16.79
14	15	14.250	0.313	0.430	0.080	130	115				10358.7	9163.5	124.76	19.33	17.99
14	17	14.283	0.314	0.460	0.086	139	127	31	258	790	11907.1	10879.2	135.20	20.91	19.48
14	19	14.317	0.316	0.470	0.088	164	158				14495.7	13965.3	145.69	22.56	21.05
14	21	14.350	0.316	0.460	0.087	149	142	29	229	585	12889.6	12284.1	155.71	24.10	22.47
14	23	14.383	0.315	0.430	0.080	160	142				12875.3	11426.8	165.59	25.44	23.69
14	25	14.417	0.315	0.450	0.084	110	104	33	173	440	9263.5	8758.2	175.50	26.67	24.80
14	27	14.450	0.316	0.430	0.081	138	120				11159.5	9703.9	185.63	28.06	26.02
14	29	14.483	0.315	0.470	0.088	137	122	32	218	390	12050.0	10730.6	195.98	29.50	27.30
14	31	14.517	0.316	0.450	0.085	141	125				11932.4	10578.4	206.03	31.49	29.08
14	33	14.550	0.316	0.440	0.083	255	230	33	246	385	21100.3	19031.7	216.04	33.55	30.93
14	35	14.583	0.315	0.450	0.084	156	138				13137.3	11621.4	225.92	35.01	30.93
14	37	14.617	0.315	0.430	0.080	141	127	31	286	480	11346.3	10219.8	235.58	36.37	32.24

Top Sampling Tube

H	M	Dec T	Depth (m)	Velocity (m/s)	Discharge (m^3/s)	TSS (mg/l)	VSS (mg/l)	Ammonia (mg/l)	BOD (mg/l)	COD (mg/l)	TSS Trans (mg/s)	VSS Trans (mg/s)	Cumm Flow (M^3)	Cumm TSS (Kg)	Cumm VSS (kg)
13	51	13.850	0.321	0.400	0.077	158	148				12177.8	11407.1	9.36	1.73	1.63
13	53	13.883	0.321	0.410	0.079	212	201	38	258	500	16748.3	15879.3	18.46	3.37	3.19
13	55	13.917	0.319	0.380	0.073	149	142				10804.8	10297.2	27.84	4.83	4.57
13	57	13.950	0.319	0.440	0.084	161	151	44	331	630	13518.4	12678.7	37.90	6.49	6.15
13	59	13.983	0.318	0.440	0.084	170	163				14204.9	13620.0	47.92	8.19	7.75
14	1	14.017	0.318	0.440	0.084	169	157	40	325	630	14121.3	13118.6	57.59	9.87	9.31
14	3	14.050	0.317	0.410	0.077	178	166				13791.8	12862.1	66.95	11.39	10.73
14	5	14.083	0.315	0.420	0.079	146	137	40	241	700	11475.5	10768.1	76.47	12.82	12.05
14	7	14.117	0.314	0.430	0.080	155	140				12411.8	11210.7	86.19	14.27	13.36
14	9	14.150	0.314	0.440	0.082	144	130	38	190	530	11799.1	10652.0	95.78	15.67	14.62
14	11	14.183	0.313	0.420	0.078	148	132				11518.8	10273.5	105.25	17.01	15.84
14	13	14.217	0.314	0.430	0.080	135	126	40	195	435	10810.3	10089.6	114.84	18.21	16.96
14	15	14.250	0.313	0.430	0.080	115	107				9163.5	8526.0	124.76	19.43	18.12
14	17	14.283	0.314	0.460	0.086	131	127	42	195	455	11221.8	10879.2	135.20	20.90	19.51
14	19	14.317	0.316	0.470	0.088	150	139				13258.2	12286.0	145.69	22.39	20.88
14	21	14.350	0.316	0.460	0.087	134	123	44	178	560	11592.0	10640.4	155.71	23.80	22.13
14	23	14.383	0.315	0.430	0.080	148	127				11909.6	10219.8	165.59	25.17	23.34
14	25	14.417	0.315	0.450	0.084	129	118	40	201	500	10863.5	9937.2	175.50	26.45	24.52
14	27	14.450	0.316	0.430	0.081	129	119				10431.7	9623.0	185.63	27.73	25.66
14	29	14.483	0.315	0.470	0.088	124	107	42	195	550	10906.6	9411.3	195.98	29.35	27.13
14	31	14.517	0.316	0.450	0.085	190	176				16079.1	14894.3	206.03	30.83	28.48
14	33	14.550	0.316	0.440	0.083	104	93	38	212	400	8605.6	7695.4	216.04	32.01	29.52
14	35	14.583	0.315	0.450	0.084	131	115				11031.9	9684.5	225.92	33.36	29.52
14	37	14.617	0.315	0.430	0.080	142	132	40	195	530	11426.8	10622.1	235.58	34.73	30.74

Study Site 3 : Sewage & Flow Data Summary

27.05.93, 48min DWF Sample

Bottom Sampling Tube

H	M	Dec T	Depth (m)	Velocity (m/s)	Discharge (m^3/s)	TSS (mg/l)	VSS (mg/l)	Ammonia (mg/l)	BOD (mg/l)	COD (mg/l)	TSS Trans (mg/s)	VSS Trans (mg/s)	Cumm Flow (M^3)	Cumm TSS (Kg)	Cumm VSS (kg)
9	41	9.68	0.331	0.480	0.097								11.20	3.20	2.98
9	43	9.72	0.328	0.450	0.090	286	266	28	448	600	25643.6	23850.4	21.79	5.89	5.47
9	45	9.75	0.326	0.440	0.087	222	205	28	828	550	19278.6	17802.4	32.42	8.51	7.89
9	47	9.78	0.325	0.460	0.090	271	249	27	380	500	24486.4	22498.6	43.29	10.66	9.87
9	49	9.82	0.326	0.460	0.091	124	116	27	390	520	11257.7	10531.4	54.09	12.93	11.95
9	51	9.85	0.327	0.450	0.089	296	269	27	397	535	26414.5	24005.1	64.89	16.21	14.98
9	53	9.88	0.326	0.460	0.091	311	292	33	425	585	28235.1	26510.1	75.50	19.48	18.02
9	55	9.92	0.324	0.440	0.086	306	281	39	448	635	26320.5	24170.1	85.82	23.06	21.35
9	57	9.95	0.324	0.440	0.086	387	364	33	440	655	33287.7	31309.3	96.50	27.14	25.21
9	59	9.98	0.324	0.470	0.092	378	359	28	431	685	34730.4	32984.7	107.43	31.06	28.85
10	1	10.02	0.325	0.460	0.090	339	308	27	434	635	30630.6	27829.6	118.45	34.84	32.33
10	3	10.05	0.327	0.470	0.093	348	323	26	436	585	32435.1	30105.0	129.51	38.17	35.39
10	5	10.08	0.327	0.460	0.091	254	231	25	430	640	23170.2	21072.1	140.36	41.50	38.49
10	7	10.12	0.328	0.450	0.090	359	339	24	425	690	32189.0	30395.8	151.27	44.79	41.57
10	9	10.15	0.329	0.460	0.092	244	227	25	440	635	22470.1	20904.6	162.41	48.60	45.19
10	11	10.18	0.328	0.470	0.094	440	422	25	453	580	41205.1	39519.5	173.65	52.74	49.10
10	13	10.22	0.328	0.470	0.094	297	275	24	450	615	27813.5	25753.2	184.51	56.24	52.31
10	15	10.25	0.327	0.440	0.087	348	316	23	448	650	30364.8	27572.6	195.31	59.71	55.50
10	17	10.28	0.326	0.470	0.093	295	275	24	448	650	27364.7	25509.5	206.29	62.84	58.38
10	19	10.32	0.325	0.460	0.090	275	248	25	448	650	24847.8	22408.2	217.14	65.40	60.71
10	21	10.35	0.325	0.460	0.090	197	183	25	488	580	17800.1	16535.1	228.10	67.98	63.10
10	23	10.38	0.325	0.470	0.092	274	252	25	368	510	25295.7	23264.6	239.41	71.02	65.73
10	25	10.42	0.325	0.490	0.096	263	213	26	400	442	25313.4	20500.9	250.87	74.18	65.73
10	27	10.45	0.326	0.480	0.095	288	264	27	436	375	27283.8	25010.1	262.24	77.45	68.46

Top Sampling Tube

H	M	Dec T	Depth (m)	Velocity (m/s)	Discharge (m^3/s)	TSS (mg/l)	VSS (mg/l)	Ammonia (mg/l)	BOD (mg/l)	COD (mg/l)	TSS Trans (mg/s)	VSS Trans (mg/s)	Cumm Flow (M^3)	Cumm TSS (Kg)	Cumm VSS (kg)
9	41	9.68	0.331	0.480	0.097								11.20	2.05	2.24
9	43	9.72	0.328	0.450	0.090	183	200	31	402	550	16408.3	17932.6	21.79	3.82	4.24
9	45	9.75	0.326	0.440	0.087	151	178				13113.0	15457.7	32.42	6.10	6.61
9	47	9.78	0.325	0.460	0.090	278	267	32	385	550	25118.9	24125.0	43.29	8.57	8.95
9	49	9.82	0.326	0.460	0.091	176	164				15978.7	14889.2	54.09	10.75	10.95
9	51	9.85	0.327	0.450	0.089	229	207	75	374	530	20435.6	18472.3	64.89	13.21	13.20
9	53	9.88	0.326	0.460	0.091	226	209				20518.1	18974.7	75.50	15.54	15.35
9	55	9.92	0.324	0.440	0.086	214	197	94	368	580	18407.1	16944.9	85.82	17.86	17.52
9	57	9.95	0.324	0.440	0.086	235	222				20213.4	19095.2	96.50	20.24	19.74
9	59	9.98	0.324	0.470	0.092	211	195	43	244	535	19386.5	17916.5	107.43	22.93	22.20
10	1	10.02	0.325	0.460	0.090	280	254				25299.6	22950.4	118.45	25.70	24.71
10	3	10.05	0.327	0.470	0.093	224	203	35	250	705	20877.8	18920.5	129.51	27.78	26.61
10	5	10.08	0.327	0.460	0.091	151	140				13774.4	12771.0	140.36	30.26	29.00
10	7	10.12	0.328	0.450	0.090	307	300	34	239	525	27526.5	26898.9	151.27	33.09	31.66
10	9	10.15	0.329	0.460	0.092	211	189				19431.1	17405.1	162.41	34.85	33.27
10	11	10.18	0.328	0.470	0.094	105	99	37	402	650	9833.0	9271.2	173.65	36.00	34.34
10	13	10.22	0.328	0.470	0.094	100	92				9364.8	8615.6	184.51	37.02	35.29
10	15	10.25	0.327	0.440	0.087	89	83	32	289	535	7765.7	7242.2	195.31	38.57	36.71
10	17	10.28	0.326	0.470	0.093	198	180				18366.8	16697.1	206.29	41.10	38.96
10	19	10.32	0.325	0.460	0.090	262	230	32	267	610	23673.2	20781.8	217.14	43.58	41.14
10	21	10.35	0.325	0.460	0.090	195	172				17619.4	15541.2	228.10	45.60	42.95
10	23	10.38	0.325	0.470	0.092	174	158	31	255	650	16063.7	14586.6	239.41	47.96	45.04
10	25	10.42	0.325	0.490	0.096	243	211				23388.4	20308.4	250.87	50.47	45.04
10	27	10.45	0.326	0.480	0.095	195	153	34	352	485	18473.4	14494.5	262.24	52.69	47.13

Constable Street Project

Sewage Pollutant Data : 08.03.95

No.	Time Hrs	Time Mins	Time Dec.	Flow V (m/s)	Flow D (m)	Flow Q (m^3/s)	TSS (mg/l)	VSS (mg/l)	Vol (%)	Ammonia (mg/l)	COD (mg/l)	BOD (mg/l)
1	11	32	11.533	0.322	0.529	0.077	201	183	91.0	12.411	605	430
2	11	34	11.567	0.310	0.529	0.074	219	199	90.9	11.920	642	-
3	11	36	11.600	0.303	0.529	0.073	195	178	91.3	11.920	588	453
4	11	38	11.633	0.308	0.529	0.074	190	175	92.1	11.920	628	-
5	11	40	11.667	0.305	0.529	0.073	174	160	92.0	11.450	610	351
6	11	42	11.700	0.298	0.528	0.072	186	165	88.7	11.450	556	-
7	11	44	11.733	0.302	0.528	0.072	193	174	90.2	11.920	791	577
8	11	46	11.767	0.313	0.527	0.075	196	178	90.8	11.920	905	-
9	11	48	11.800	0.308	0.527	0.074	195	174	89.2	11.920	905	758
10	11	50	11.833	0.318	0.526	0.076	197	175	88.8	11.450	748	-
11	11	52	11.867	0.317	0.526	0.076	243	216	88.9	12.410	1471	566
12	11	54	11.900	0.305	0.526	0.073	194	181	93.3	12.410	950	-
13	11	56	11.933	0.328	0.525	0.078	193	177	91.7	11.450	714	441
14	11	58	11.967	0.328	0.525	0.078	177	165	93.2	11.450	940	-
15	12	0	12.000	0.322	0.525	0.077	169	149	88.2	10.995	683	396
16	12	2	12.033	0.323	0.525	0.077	174	158	90.8	10.995	597	-
17	12	4	12.067	0.312	0.524	0.074	173	154	89.0	10.559	733	486
18	12	6	12.100	0.307	0.524	0.073	166	148	89.2	10.559	1137	-
19	12	8	12.133	0.308	0.524	0.074	172	155	90.1	10.559	610	419
20	12	10	12.167	0.308	0.524	0.073	172	166	96.5	10.141	704	-
21	12	12	12.200	0.317	0.524	0.076	177	159	89.8	9.740	536	385
22	12	14	12.233	0.323	0.523	0.077	186	165	88.7	9.740	617	-
23	12	16	12.267	0.317	0.523	0.076	172	152	88.4	9.740	631	520
24	12	18	12.300	0.317	0.523	0.075	171	148	86.5	9.740	627	-
		Averages ->		0.313	0.526	0.075	186.9	168.9	90.4	11.2	747.0	481.7

Cumulative Transport Rates

Bed-Load Dry wt

0.902 kg

Tot B-L : Tot SS

0.022

Tot B-L / Tot Soilds

2.193 %

B-L Conc

4.2 mg/l

Time	B-L (kg)	Q (m^3/2 min)	Cumulative Q (m^3)	Cumulative TSS (kg)	Cumulative VSS (kg)	Cumulative Ammonia (kg)	Cumulative COD (kg)	Cumulative BOD (kg)
11.53	0.038	9.07	9.07	1.82	1.66	0.11	5.49	3.90
11.57	0.075	8.81	17.88	3.75	3.41	0.22	11.14	
11.60	0.113	8.79	26.67	5.47	4.98	0.32	16.56	11.86
11.63	0.150	8.81	35.48	7.14	6.52	0.43	21.90	
11.67	0.188	8.67	44.15	8.65	7.91	0.53	27.36	18.00
11.70	0.226	8.62	52.77	10.25	9.33	0.63	32.41	
11.73	0.263	8.82	61.59	11.95	10.86	0.73	38.22	28.05
11.77	0.301	8.91	70.50	13.70	12.45	0.84	45.70	
11.80	0.338	8.99	79.49	15.45	14.01	0.94	53.76	41.62
11.83	0.376	9.12	88.61	17.25	15.61	1.05	61.19	
11.87	0.413	8.92	97.53	19.42	17.54	1.16	71.31	51.82
11.90	0.451	9.07	106.60	21.18	19.18	1.27	82.11	
11.93	0.489	9.40	116.00	22.99	20.84	1.38	89.65	59.97
11.97	0.526	9.30	125.30	24.64	22.38	1.49	97.43	
12.00	0.564	9.22	134.52	26.20	23.75	1.59	104.97	67.30
12.03	0.601	9.07	143.59	27.77	25.18	1.69	110.88	
12.07	0.639	8.84	152.43	29.30	26.54	1.78	116.91	76.01
12.10	0.677	8.80	161.23	30.76	27.85	1.87	125.17	
12.13	0.714	8.81	170.04	32.28	29.21	1.97	132.86	83.38
12.17	0.752	8.93	178.97	33.82	30.70	2.06	138.65	
12.20	0.789	9.16	188.13	35.44	32.15	2.15	144.18	90.34
12.23	0.827	9.16	197.29	37.14	33.66	2.24	149.47	
12.27	0.864	9.05	206.34	38.70	35.04	2.32	155.18	104.50
12.30	0.902	9.01	215.35	40.24	36.37	2.41	160.87	109.18
		Rate (g/s) ->		13.97	12.63	0.84	55.86	37.86

Constable Street Project

Sewage Pollutant Data : 15.03.95

No.	Time			Flow			TSS	VSS	Vol	Ammonia	COD	BOD
	Hrs	Mins	Dec.	V (m/s)	D (m)	Q (m^3/s)	(mg/l)	(mg/l)	(%)	(mg/l)	(mg/l)	(mg/l)
1	10	56	10.933	0.330	0.547	0.081	272	242	89.0		716	503
2	10	58	10.967	0.330	0.544	0.081	252	224	88.9		778	-
3	11	0	11.000	0.330	0.543	0.081	275	246	89.5		665	480
4	11	2	11.033	0.322	0.544	0.079	253	226	89.3		721	-
5	11	4	11.067	0.325	0.545	0.080	265	236	89.1		788	
6	11	6	11.100	0.330	0.544	0.081	277	246	88.8		855	458
7	11	8	11.133	0.323	0.543	0.079	271	246	90.8		672	458
8	11	10	11.167	0.325	0.546	0.079	262	238	90.8		799	-
9	11	12	11.200	0.332	0.547	0.081	249	226	90.8		708	480
10	11	14	11.233	0.332	0.547	0.081	268	246	91.8		1029	-
11	11	16	11.267	0.325	0.545	0.080	228	207	90.8		635	447
12	11	18	11.300	0.325	0.544	0.080	221	202	91.4		623	-
13	11	20	11.333	0.327	0.545	0.080	211	192	91.0		703	480
14	11	22	11.367	0.318	0.549	0.078	217	199	91.7		687	-
15	11	24	11.400	0.322	0.550	0.079	220	201	91.4		720	447
16	11	26	11.433	0.325	0.547	0.080	239	214	89.5		874	-
17	11	28	11.467	0.325	0.544	0.079	265	245	92.5		638	492
18	11	30	11.500	0.322	0.544	0.079	208	190	91.3		648	-
19	11	32	11.533	0.317	0.547	0.077	265	238	89.8		806	458
20	11	34	11.567	0.317	0.547	0.077	236	210	89.0		738	-
21	11	36	11.600	0.320	0.546	0.078	222	199	89.6		723	435
22	11	38	11.633	0.327	0.546	0.080	237	211	89.0		725	-
23	11	40	11.667	0.327	0.546	0.080	229.5	205	89.325		724	447
24	11	42	11.700	0.327	0.545	0.080	229.5	205	89.325		724	-
	Averages ->			0.325	0.546	0.079	244.7	220.6	90.2		737.5	465.3

Cumulative Transport Rates

Bed-Load Dry wt

0.766 kg

Tot B-L : Tot SS

0.014

Tot B-L / Tot Soilds

1.35 %

B-L Conc

3.3 mg/l

Time	B-L	Q	Cumulative					
	(kg)	(m^3/2 min)	Q (m^3)	TSS (kg)	VSS (kg)	Ammonia (kg)	COD (kg)	BOD (kg)
10.93	0.032	9.70	9.70	2.64	2.35		6.95	4.88
10.97	0.064	9.68	19.38	5.08	4.52		14.19	
11.00	0.096	9.54	28.92	7.70	6.86		21.18	14.11
11.03	0.128	9.48	38.40	10.10	9.01		27.79	
11.07	0.160	9.61	48.01	12.65	11.27		34.94	22.85
11.10	0.192	9.57	57.58	15.30	13.63		42.83	
11.13	0.223	9.49	67.07	17.87	15.96		50.14	31.58
11.17	0.255	9.64	76.71	20.39	18.26		57.12	
11.20	0.287	9.75	86.46	22.82	20.46		64.38	40.89
11.23	0.319	9.64	96.10	25.41	22.83		72.85	
11.27	0.351	9.54	105.64	27.58	24.81		80.87	49.46
11.30	0.383	9.56	115.20	29.69	26.74		86.87	
11.33	0.415	9.47	124.67	31.69	28.56		93.21	58.60
11.37	0.447	9.41	134.08	33.73	30.43		99.79	
11.40	0.479	9.50	143.58	35.82	32.34		106.41	67.04
11.43	0.511	9.53	153.11	38.10	34.38		113.98	
11.47	0.543	9.47	162.58	40.61	36.70		121.19	76.38
11.50	0.575	9.35	171.93	42.56	38.47		127.28	
11.53	0.606	9.28	181.21	45.02	40.68		134.08	84.91
11.57	0.638	9.33	190.54	47.22	42.64		141.24	
11.60	0.670	9.48	200.02	49.32	44.53		148.06	93.10
11.63	0.702	9.58	209.60	51.59	46.55		154.92	
11.67	0.734	9.58	219.18	53.79	48.51		161.86	105.92
11.70	0.766	9.56	228.74	55.98	50.47		168.80	110.19
		Rate (g/s) ->		19.44	17.53		58.61	38.38

Constable Street Project

Sewage Pollutant Data : 22.03.95

No.	Time			Flow			TSS	VSS	Vol	Ammonia	COD	BOD
	Hrs	Mins	Dec.	V (m/s)	D (m)	Q (m^3/s)	(mg/l)	(mg/l)	(%)	(mg/l)	(mg/l)	(mg/l)
1	12	39	12.650	0.263	0.526	0.063	221	201	91.0	21.162	684	492
2	12	41	12.683	0.263	0.527	0.063	224	209	93.3	19.513	937	
3	12	43	12.717	0.260	0.528	0.063	250	232	92.8	19.513	710	481
4	12	45	12.750	0.263	0.529	0.063	242	232	95.9	18.737	712	
5	12	47	12.783	0.267	0.529	0.064	279	269	96.4	17.992	680	435
6	12	49	12.817	0.267	0.528	0.064	294	283	96.3	18.737	726	
7	12	51	12.850	0.270	0.528	0.065	300	284	94.7	19.513	771	435
8	12	53	12.883	0.270	0.528	0.065	215	203	94.4	19.513	650	
9	12	55	12.917	0.273	0.529	0.066	222	213	95.9	19.513	665	345
10	12	57	12.950	0.273	0.529	0.066	191	180	94.2	19.513	621	
11	12	59	12.983	0.273	0.528	0.066	221	207	93.7	20.321	602	390
12	13	1	13.017	0.273	0.528	0.066	203	192	94.6	20.321	654	
13	13	3	13.050	0.270	0.528	0.065	222	207	93.2	21.162	623	368
14	13	5	13.083	0.260	0.528	0.063	251	240	95.6	21.162	597	
15	13	7	13.117	0.263	0.528	0.064	206	194	94.2	21.162	640	424
16	13	9	13.150	0.270	0.526	0.065	240	228	95.0	21.162	628	
17	13	11	13.183	0.263	0.525	0.063	227	212	93.4	20.321	650	390
18	13	13	13.217	0.270	0.525	0.065	215	202	94.0	20.321	532	
19	13	15	13.250	0.270	0.526	0.065	226	208	92.0	22.038	637	413
20	13	17	13.283	0.273	0.526	0.066	255	237	92.9	22.951	683	
21	13	19	13.317	0.277	0.526	0.066	231	179	77.5	22.038	693	435
22	13	21	13.350	0.270	0.525	0.065	228	213	93.4	21.162	685	
23	13	23	13.383	0.270	0.526	0.065	322	272	84.5	21.162	749	435
24	13	25	13.417	0.267	0.527	0.064	337	310	92.0	22.951	739	
		Averages ->		0.268	0.527	0.065	242.6	225.3	93.0	20.5	677.8	420.3

Cumulative Transport Rates

	Time	B-L	Q	Cumulative					
		(kg)	(m^3/2 min)	Q (m^3)	TSS (kg)	VSS (kg)	Ammonia (kg)	COD (kg)	BOD (kg)
Bed-Load Dry wt	12.65	0.047	7.60	7.60	1.68	1.53	0.16	5.20	3.74
1.138 kg	12.68	0.095	7.56	15.16	3.37	3.11	0.31	11.36	
	12.72	0.142	7.56	22.72	5.26	4.86	0.46	17.58	11.01
	12.75	0.190	7.64	30.36	7.11	6.64	0.60	22.96	
Tot B-L : Tot SS	12.78	0.237	7.68	38.04	9.26	8.70	0.74	28.28	11.01
	12.82	0.284	7.74	45.78	11.53	10.89	0.88	33.68	
0.025	12.85	0.332	7.80	53.58	13.87	13.11	1.03	39.47	17.77
	12.88	0.379	7.84	61.42	15.56	14.70	1.19	45.01	
	12.92	0.427	7.88	69.30	17.31	16.38	1.34	50.17	23.19
Tot B-L / Tot Soilds	12.95	0.474	7.88	77.18	18.81	17.80	1.49	55.23	
	12.98	0.521	7.88	85.06	20.55	19.43	1.66	60.05	29.34
2.462 %	13.02	0.569	7.84	92.90	22.15	20.93	1.81	65.00	
	13.05	0.616	7.66	100.56	23.85	22.52	1.98	70.01	35.04
	13.08	0.664	7.58	108.14	25.75	24.34	2.14	74.68	
B-L Conc	13.12	0.711	7.70	115.84	27.33	25.83	2.30	79.37	41.52
	13.15	0.758	7.68	123.52	29.18	27.58	2.46	84.25	
6.1 mg/l	13.18	0.806	7.70	131.22	30.93	29.21	2.62	89.16	47.52
	13.22	0.853	7.78	139.00	32.60	30.79	2.78	93.71	
	13.25	0.901	7.82	146.82	34.37	32.41	2.95	98.25	53.96
	13.28	0.948	7.92	154.74	36.39	34.29	3.13	103.41	
	13.32	0.995	7.86	162.60	38.20	35.70	3.30	108.86	60.83
	13.35	1.043	7.76	170.36	39.97	37.35	3.47	114.28	
	13.38	1.090	7.74	178.10	42.46	39.45	3.63	119.84	70.95
	13.42	1.138	7.73	185.83	45.07	41.85	3.81	125.60	74.31
			Rate (g/s) ->		15.65	14.53	1.32	43.61	25.71

Constable Street Project

Sewage Pollutant Data : 29.03.95

No.	Time			Flow			TSS	VSS	Vol	Ammonia	COD	BOD
	Hrs	Mins	Dec.	V (m/s)	D (m)	Q (m^3/s)	(mg/l)	(mg/l)	(%)	(mg/l)	(mg/l)	(mg/l)
1	10	7	10.117	0.263	0.540	0.064	257	227	88.3	24.5	581	329
2	10	9	10.150	0.260	0.543	0.064	282	254	90.1	23.5	616	
3	10	11	10.183	0.267	0.547	0.065	252	225	89.3	23.5	641	351
4	10	13	10.217	0.265	0.549	0.065	249	220	88.4	22.5	691	
5	10	15	10.250	0.257	0.543	0.063	280	245	87.5	22.5	584	283
6	10	17	10.283	0.260	0.541	0.064	269	234	87.0	21.6	611	
7	10	19	10.317	0.267	0.543	0.065	251	220	87.6	21.6	686	340
8	10	21	10.350	0.263	0.543	0.064	252	223	88.5	20.7	653	
9	10	23	10.383	0.258	0.544	0.063	248	220	88.7	21.6	622	272
10	10	25	10.417	0.257	0.547	0.063	263	237	90.1	21.6	623	
11	10	27	10.450	0.263	0.546	0.064	283	259	91.5	21.6	617	306
12	10	29	10.483	0.260	0.541	0.063	274	246	89.8	22.5	671	
13	10	31	10.517	0.265	0.542	0.065	268	242	90.3	21.6	641	329
14	10	33	10.550	0.263	0.544	0.064	256	231	90.2	21.6	701	
15	10	35	10.583	0.270	0.542	0.066	264	240	90.9	21.6	897	374
16	10	37	10.617	0.272	0.542	0.066	249	216	86.7	21.6	664	
17	10	39	10.650	0.257	0.542	0.063	263.6	235.0	89.1	22.1	663.9	321.1
18	10	41	10.683	0.258	0.543	0.063	263.6	235.0	89.1	22.1	663.9	
19	10	43	10.717	0.268	0.546	0.066	263.6	235.0	89.1	22.1	663.9	321.1
20	10	45	10.750	0.262	0.547	0.064	263.6	235.0	89.1	22.1	663.9	
21	10	47	10.783	0.262	0.547	0.064	263.6	235.0	89.1	22.1	663.9	321.1
22	10	49	10.817	0.253	0.546	0.062	263.6	235.0	89.1	22.1	663.9	
23	10	51	10.850	0.265	0.553	0.065	292	262	89.726	21.6	850	306
24	10	53	10.883	0.270	0.549	0.066	256	229	89.453	21.6	602	
	Averages ->			0.263	0.544	0.064	263.6	235.0	89.1	22.1	663.9	321.1

Cumulative Transport Rates

Bed-Load Dry wt

1.322 kg

Tot B-L : Tot SS

0.027

Tot B-L / Tot Solids

2.641 %

B-L Conc

7.2 mg/l

Time	B-L	Q	Cumulative					
	(kg)	(m^3/2 min)	Q (m^3)	TSS (kg)	VSS (kg)	Ammonia (kg)	COD (kg)	BOD (kg)
10.12	0.055	7.66	7.66	1.97	1.74	0.19	4.45	2.52
10.15	0.110	7.73	15.39	4.15	3.70	0.37	9.03	
10.18	0.165	7.82	23.21	6.12	5.46	0.55	13.89	7.98
10.22	0.220	7.66	30.87	8.03	7.15	0.73	19.10	
10.25	0.275	7.57	38.44	10.15	9.00	0.90	23.98	7.98
10.28	0.331	7.72	46.16	12.22	10.81	1.06	28.51	
10.32	0.386	7.77	53.93	14.17	12.52	1.23	33.51	13.24
10.35	0.441	7.64	61.57	16.10	14.22	1.39	38.72	
10.38	0.496	7.54	69.11	17.97	15.88	1.55	43.59	17.37
10.42	0.551	7.61	76.72	19.97	17.68	1.72	48.28	
10.45	0.606	7.64	84.36	22.13	19.66	1.88	53.00	22.04
10.48	0.661	7.67	92.03	24.23	21.55	2.05	57.92	
10.52	0.716	7.74	99.77	26.31	23.42	2.22	62.95	27.10
10.55	0.771	7.82	107.59	28.31	25.23	2.39	68.14	
10.58	0.826	7.93	115.52	30.40	27.13	2.56	74.39	32.99
10.62	0.881	7.72	123.24	32.33	28.80	2.73	80.58	
10.65	0.936	7.54	130.78	34.31	30.57	2.90	85.71	37.89
10.68	0.992	7.73	138.51	36.35	32.39	3.07	90.71	
10.72	1.047	7.79	146.30	38.40	34.22	3.24	95.84	42.87
10.75	1.102	7.70	154.00	40.43	36.03	3.41	101.02	
10.78	1.157	7.57	161.57	42.43	37.81	3.58	106.13	47.78
10.82	1.212	7.62	169.19	44.44	39.60	3.74	111.15	
10.85	1.267	7.87	177.06	46.74	41.66	3.91	116.92	54.91
10.88	1.322	7.82	184.88	48.74	43.45	4.08	122.64	57.30
		Rate (g/s) ->		16.92	15.09	1.42	42.58	19.90

Constable Street Project

Sewage Pollutant Data : 06.04.95

No.	Time			Flow			TSS	VSS	Vol	Ammonia	COD	BOD
	Hrs	Mins	Dec.	V (m/s)	D (m)	Q (m^3/s)	(mg/l)	(mg/l)	(%)	(mg/l)	(mg/l)	(mg/l)
1	9	40	9.667	0.243	0.533	0.059	250	185	74.0	9.206	608	515
2	9	42	9.700	0.245	0.533	0.059	234	202	86.3	8.270	754	
3	9	44	9.733	0.248	0.533	0.059	214	209	97.7	7.838	768	470
4	9	46	9.767	0.247	0.532	0.059	231	247	106.9	7.429	720	
5	9	48	9.800	0.238	0.532	0.060	210	195	92.9	7.429	768	470
6	9	50	9.833	0.243	0.533	0.060	218	217	99.5	7.429	815	
7	9	52	9.867	0.242	0.533	0.060	298	300	100.7	7.429	815	493
8	9	54	9.900	0.240	0.532	0.058	220	182	82.7	7.838	603	
9	9	56	9.933	0.243	0.532	0.058	244	212	86.9	7.429	671	515
10	9	58	9.967	0.245	0.532	0.058	247	191	77.3	7.429	731	
11	10	0	10.000	0.245	0.531	0.059	223	219	98.2	7.429	675	481
12	10	2	10.033	0.245	0.531	0.059	247	190	76.9	7.429	652	
13	10	4	10.067	0.245	0.528	0.058	253	212	83.8	7.429	632	515
14	10	6	10.100	0.243	0.525	0.057	241	236	97.9	7.041	662	
15	10	8	10.133	0.247	0.521	0.057	233	215	92.3	7.041	745	538
16	10	10	10.167	0.245	0.521	0.058	236	248	105.1	7.041	766	
17	10	12	10.200	0.247	0.520	0.058	225	191	84.9	7.041	621	470
18	10	14	10.233	0.240	0.520	0.058	223	236	105.8	7.041	680	
19	10	16	10.267	0.243	0.521	0.058	305	326	106.9	7.041	662	470
20	10	18	10.300	0.240	0.522	0.059	232	222	95.7	6.674	811	
21	10	20	10.333	0.245	0.524	0.059	224	191	85.3	6.674	761	504
22	10	22	10.367	0.243	0.526	0.058	214	160	74.8	7.041	718	
23	10	24	10.400	0.243	0.527	0.059	214	189	88.3	7.041	617	470
24	10	26	10.433	0.248	0.527	0.059	227	184	81.1	7.041	686	
		Averages ->		0.244	0.528	0.058	236.0	215.0	90.9	7.4	705.9	492.7

Cumulative Transport Rates

Bed-Load Dry wt

1.314 kg

Tot B-L : Tot SS

0.033

Tot B-L / Tot Soilds

3.202 %

B-L Conc

7.8 mg/l

			Cumulative					
Time	B-L (kg)	Q (m^3/2 min)	Q (m^3)	TSS (kg)	VSS (kg)	Ammonia (kg)	COD (kg)	BOD (kg)
9.67	0.055	7.08	7.08	1.77	1.31	0.07	4.30	3.65
9.70	0.110	7.10	14.18	3.43	2.74	0.12	9.13	
9.73	0.164	7.11	21.29	4.95	4.23	0.18	14.53	10.33
9.77	0.219	7.15	28.44	6.60	6.00	0.23	19.82	
9.80	0.274	7.18	35.62	8.11	7.40	0.29	25.14	10.33
9.83	0.329	7.16	42.78	9.67	8.95	0.34	30.82	
9.87	0.383	7.08	49.86	11.78	11.07	0.39	36.66	17.34
9.90	0.438	6.95	56.81	13.31	12.34	0.45	41.68	
9.93	0.493	6.92	63.73	15.00	13.81	0.50	46.10	24.49
9.97	0.548	6.99	70.72	16.73	15.14	0.55	50.95	
10.00	0.602	7.06	77.78	18.30	16.69	0.60	55.87	31.26
10.03	0.657	7.02	84.80	20.04	18.02	0.65	60.55	
10.07	0.712	6.90	91.70	21.78	19.48	0.71	65.06	38.43
10.10	0.767	6.85	98.55	23.43	21.10	0.75	69.52	
10.13	0.821	6.89	105.44	25.04	22.58	0.80	74.34	45.82
10.17	0.876	6.94	112.38	26.68	24.30	0.85	79.55	
10.20	0.931	6.94	119.32	28.24	25.63	0.90	84.36	52.34
10.23	0.986	6.96	126.28	29.79	27.27	0.95	88.88	
10.27	1.040	7.01	133.29	31.93	29.56	1.00	93.55	58.91
10.30	1.095	7.02	140.31	33.56	31.11	1.05	98.71	
10.33	1.150	6.99	147.30	35.12	32.45	1.09	104.23	65.97
10.37	1.205	7.01	154.31	36.62	33.57	1.14	109.40	
10.40	1.260	7.06	161.37	38.13	34.91	1.19	114.07	75.90
10.43	1.314	7.04	168.41	39.73	36.20	1.24	118.67	79.20
		Rate (g/s) ->		13.80	12.57	0.43	41.21	27.50

Constable Street Project

Sewage Pollutant Data : **12.04.95**

No.	Time Hrs	Time Mins	Time Dec.	Flow V (m/s)	Flow D (m)	Flow Q (m^3/s)	TSS (mg/l)	VSS (mg/l)	Vol (%)	Ammonia (mg/l)	COD (mg/l)	BOD (mg/l)
1	9	26	9.433	0.272	0.522	0.065	314	288	91.7	18.464	691	667
2	9	28	9.467	0.270	0.521	0.064	259	238	91.9	17.733	815	
3	9	30	9.500	0.258	0.522	0.061	254	226	89.0	17.031	752	724
4	9	32	9.533	0.258	0.522	0.062	299	262	87.6	17.031	766	
5	9	34	9.567	0.258	0.521	0.062	281	250	89.0	17.733	770	690
6	9	36	9.600	0.263	0.522	0.063	310	278	89.7	17.031	679	
7	9	38	9.633	0.258	0.522	0.062	329	300	91.2	17.031	695	566
8	9	40	9.667	0.255	0.523	0.061	287	265	92.3	17.031	679	
9	9	42	9.700	0.257	0.524	0.062	317	290	91.5	17.031	648	532
10	9	44	9.733	0.263	0.524	0.063	290	268	92.4	16.356	463	
11	9	46	9.767	0.262	0.520	0.062	271	246	90.8	15.709	711	554
12	9	48	9.800	0.255	0.520	0.061	273	250	91.6	15.087	678	
13	9	50	9.833	0.252	0.522	0.060	281	258	91.8	14.490	655	498
14	9	52	9.867	0.250	0.523	0.060	273	249	91.2	14.490	690	
15	9	54	9.900	0.253	0.523	0.061	261	240	92.0	13.916	622	543
16	9	56	9.933	0.255	0.522	0.061	272	250	91.9	13.916	626	
17	9	58	9.967	0.255	0.523	0.061	316	288	91.1	13.916	636	543
18	10	0	10.000	0.252	0.526	0.061	289	259	89.6	13.916	705	
19	10	2	10.033	0.253	0.523	0.061	316	255	80.7	13.365	626	634
20	10	4	10.067	0.262	0.521	0.062	302	271	89.7	13.365	652	
21	10	6	10.100	0.262	0.522	0.062	282	262	92.9	13.365	696	509
22	10	8	10.133	0.255	0.521	0.061	301	272	90.4	13.365	713	
23	10	10	10.167	0.257	0.520	0.061	288	263	91.3	13.365	613	475
24	10	12	10.200	0.253	0.519	0.060	256	237	92.6	13.365	716	
	Averages ->			0.258	0.522	0.061	288.4	261.0	90.6	15.3	679.0	577.9

Cumulative Transport Rates

Bed-Load Dry wt

0.871 kg

Tot B-L : Tot SS

0.017

Tot B-L / Tot Soilds

1.679 %

B-L Conc

4.9 mg/l

Time	B-L (kg)	Q (m^3/2 min)	Cumulative Q (m^3)	Cumulative TSS (kg)	Cumulative VSS (kg)	Cumulative Ammonia (kg)	Cumulative COD (kg)	Cumulative BOD (kg)
9.43	0.036	7.75	7.75	2.43	2.23	0.14	5.36	5.17
9.47	0.073	7.54	15.29	4.39	4.03	0.28	11.19	
9.50	0.109	7.38	22.67	6.26	5.69	0.40	17.10	15.97
9.53	0.145	7.40	30.07	8.47	7.63	0.53	22.70	
9.57	0.181	7.47	37.54	10.57	9.50	0.66	28.38	15.97
9.60	0.218	7.46	45.00	12.89	11.57	0.79	33.80	
9.63	0.254	7.33	52.33	15.30	13.77	0.91	38.92	24.34
9.67	0.290	7.33	59.66	17.40	15.72	1.04	43.96	
9.70	0.327	7.47	67.13	19.77	17.88	1.16	48.82	32.21
9.73	0.363	7.51	74.64	21.95	19.90	1.29	52.97	
9.77	0.399	7.37	82.01	23.94	21.71	1.40	57.38	40.46
9.80	0.436	7.24	89.25	25.92	23.52	1.51	62.50	
9.83	0.472	7.18	96.43	27.94	25.37	1.62	67.32	47.64
9.87	0.508	7.21	103.64	29.91	27.17	1.72	72.15	
9.90	0.544	7.27	110.91	31.80	28.91	1.82	76.88	55.50
9.93	0.581	7.29	118.20	33.79	30.73	1.92	81.42	
9.97	0.617	7.28	125.48	36.09	32.83	2.03	86.02	63.42
10.00	0.653	7.26	132.74	38.18	34.71	2.13	90.90	
10.03	0.690	7.37	140.11	40.51	36.59	2.22	95.73	72.68
10.07	0.726	7.47	147.58	42.77	38.61	2.32	100.44	
10.10	0.762	7.36	154.94	44.85	40.54	2.42	105.47	80.24
10.13	0.799	7.30	162.24	47.04	42.53	2.52	110.66	
10.17	0.835	7.28	169.52	49.14	44.44	2.62	115.50	90.63
10.20	0.871	7.30	176.82	51.01	46.17	2.72	120.34	94.10
		Rate (g/s) ->		17.71	16.03	0.94	41.78	32.84

Constable Street Project

Sewage Pollutant Data : 26.04.95

No.	Time Hrs	Time Mins	Time Dec.	Flow V (m/s)	Flow D (m)	Flow Q (m^3/s)	TSS (mg/l)	VSS (mg/l)	Vol (%)	Ammonia (mg/l)	COD (mg/l)	BOD (mg/l)
1	10	17	10.283	0.273	0.513	0.064	306	273	89.2	14.490	668	566
2	10	19	10.317	0.277	0.516	0.065	270.9	236.3	87.5	11.700	691.8	
3	10	21	10.350	0.273	0.518	0.065	285	260	91.2	12.836	591	611
4	10	23	10.383	0.273	0.518	0.065	236	211	89.4	11.840	684	
5	10	25	10.417	0.277	0.521	0.066	290	259	89.3	12.328	744	600
6	10	27	10.450	0.277	0.517	0.066	270.9	236.3	87.5	11.700	691.84	
7	10	29	10.483	0.277	0.517	0.066	248	224	90.3	11.371	679	566
8	10	31	10.517	0.275	0.515	0.065	264	237	89.8	11.371	681	
9	10	33	10.550	0.278	0.514	0.066	267	234	87.6	11.371	684	566
10	10	35	10.583	0.275	0.511	0.065	285	241	84.6	11.700	691.84	
11	10	37	10.617	0.270	0.516	0.064	270.9	236.3	87.5	11.700	691.84	542
12	10	39	10.650	0.275	0.518	0.065	270.9	236.3	87.5	11.700	691.84	
13	10	41	10.683	0.278	0.516	0.066	336	284	84.7	11.700	671	566
14	10	43	10.717	0.282	0.512	0.066	262	230	87.8	11.371	705	
15	10	45	10.750	0.280	0.515	0.066	264	227	86.0	11.840	794	634
16	10	47	10.783	0.275	0.505	0.064	316	279	88.3	11.700	799	
17	10	49	10.817	0.277	0.495	0.063	245	216	88.2	11.371	680	769
18	10	51	10.850	0.275	0.498	0.063	282	242	85.8	11.371	745	
19	10	53	10.883	0.273	0.512	0.064	260	236	90.8	11.371	737	532
20	10	55	10.917	0.272	0.522	0.065	251	223	88.8	11.371	721	
21	10	57	10.950	0.272	0.512	0.064	256	214	83.6	11.371	664	543
22	10	59	10.983	0.273	0.499	0.063	255	213	83.5	10.921	608	
23	11	1	11.017	0.273	0.493	0.063	253	215	85.0	11.371	661	554
24	11	3	11.050	0.272	0.494	0.062	261	225	86.2	10.921	629	
		Averages ->		0.275	0.511	0.065	270.9	237.0	87.5	11.7	691.8	587.3

Cumulative Transport Rates

Bed-Load Dry wt

0.767 kg

Tot B-L : Tot SS

0.015

Tot B-L / Tot Soilds

1.497 %

B-L Conc

4.1 mg/l

Time	B-L (kg)	Q (m^3/2 min)	Cumulative Q (m^3)	Cumulative TSS (kg)	Cumulative VSS (kg)	Cumulative Ammonia (kg)	Cumulative COD (kg)	Cumulative BOD (kg)
10.28	0.032	7.77	7.77	2.38	2.12	0.11	5.19	4.40
10.32	0.064	7.81	15.58	4.49	3.97	0.20	10.47	
10.35	0.096	7.78	23.36	6.71	5.99	0.30	15.48	13.92
10.38	0.128	7.84	31.20	8.56	7.64	0.40	20.44	
10.42	0.160	7.89	39.09	10.85	9.69	0.49	26.04	13.92
10.45	0.192	7.89	46.98	12.99	11.55	0.59	31.70	
10.48	0.224	7.85	54.83	14.93	13.31	0.68	37.11	22.82
10.52	0.256	7.84	62.67	17.00	15.17	0.76	42.45	
10.55	0.287	7.82	70.49	19.09	17.00	0.85	47.80	31.68
10.58	0.319	7.71	78.20	21.29	18.86	0.94	53.18	
10.62	0.351	7.75	85.95	23.39	20.69	1.03	58.52	40.06
10.65	0.383	7.87	93.82	25.52	22.55	1.13	63.88	
10.68	0.415	7.92	101.74	28.18	24.80	1.22	69.24	49.00
10.72	0.447	7.94	109.68	30.26	26.63	1.31	74.69	
10.75	0.479	7.81	117.49	32.32	28.40	1.40	80.64	58.97
10.78	0.511	7.64	125.13	34.74	30.53	1.49	86.86	
10.82	0.543	7.60	132.73	36.60	32.17	1.58	92.51	70.69
10.85	0.575	7.65	140.38	38.76	34.02	1.66	97.93	
10.88	0.607	7.73	148.11	40.77	35.85	1.75	103.59	78.87
10.92	0.639	7.72	155.83	42.70	37.57	1.84	109.23	
10.95	0.671	7.63	163.46	44.66	39.20	1.93	114.58	87.21
10.98	0.703	7.54	171.00	46.58	40.81	2.01	119.43	
11.02	0.735	7.47	178.47	48.47	42.41	2.09	124.21	99.74
11.05	0.767	7.60	186.07	50.45	44.12	2.18	129.03	103.95
		Rate (g/s) ->		17.52	15.32	0.76	44.80	36.14

Constable Street Project

Sewage Pollutant Data : 03.05.95

No.	Time			Flow			TSS	VSS	Vol	Ammo	COD	BOD
	Hrs	Mins	Dec.	V (m/s)	D (m)	Q (m^3/s)	(mg/l)	(mg/l)	(%)	(mg/l)	(mg/l)	(mg/l)
1	9	47	9.783	0.278	0.514	0.066	395	341	86	27.420	871	685
2	9	49	9.817	0.278	0.521	0.066	414	354	88	26.316	890.0	
3	9	51	9.850	0.278	0.519	0.066	453	379	84	25.256	918	662
4	9	53	9.883	0.277	0.517	0.066	476	372	78	25.256	900	
5	9	55	9.917	0.270	0.517	0.064	488	345	71	24.239	850	662
6	9	57	9.950	0.265	0.516	0.063	539	379	88	24.239	1123	
7	9	59	9.983	0.278	0.521	0.066	488	363	74	23.262	905	640
8	10	1	10.017	0.273	0.518	0.065	433	324	75	22.325	898	
9	10	3	10.050	0.263	0.515	0.062	444	341	77	21.426	700	606
10	10	5	10.083	0.268	0.515	0.064	399	312	78	21.426	742	
11	10	7	10.117	0.273	0.516	0.065	386	307	88	21.426	841	617
12	10	9	10.150	0.275	0.519	0.066	536	441	88	20.563	778	
13	10	11	10.183	0.270	0.519	0.064	365	296	81	20.563	855.0	685
14	10	13	10.217	0.278	0.519	0.066	357	294	82	20.563	808.0	
15	10	15	10.250	0.273	0.521	0.065	335	285	85	19.735	674.0	606
16	10	17	10.283	0.273	0.511	0.064	348	286	82	20.563	756.0	
17	10	19	10.317	0.273	0.501	0.063	417	333	82	14.203	834.4	606
18	10	21	10.350	0.270	0.508	0.063	417	333	82	14.203	834.4	
19	10	23	10.383	0.267	0.522	0.064	417	333	82	14.203	834.4	606
20	10	25	10.417	0.268	0.528	0.065	417	333	82	14.203	834.4	
21	10	27	10.450	0.265	0.530	0.064	417	333	82	14.203	834.4	606
22	10	29	10.483	0.262	0.530	0.063	289	252	87	18.940	819.0	
23	10	31	10.517	0.267	0.528	0.065	425	360	85	18.940	793	606
24	10	33	10.550	0.268	0.523	0.065	359	289	81	18.940	733	
		Averages ->		0.271	0.518	0.065	417.3	332.6	81.9	14.2	834.4	632.3

Cumulative Transport Rates

Bed-Load Dry wt

0.367 kg

Tot B-L : Tot SS

0.004731

Tot B-L / Tot Soilds

0.470857 %

B-L Conc

2.0 mg/l

Time	B-L	Q	Cumulative					
			Q	TSS	VSS	Ammo	COD	BOD
	(kg)	(m^3/2 min)	(m^3)	(kg)	(kg)	(kg)	(kg)	(kg)
9.78	0.015	7.92	7.92	3.13	2.70	0.22	6.90	5.43
9.82	0.031	7.95	15.87	6.42	5.52	0.43	13.87	
9.85	0.046	7.92	23.79	10.01	8.52	0.63	21.06	15.94
9.88	0.061	7.80	31.59	13.72	11.42	0.82	28.26	
9.92	0.076	7.63	39.22	17.44	14.05	1.01	35.08	26.16
9.95	0.092	7.76	46.98	21.63	16.99	1.20	42.61	
9.98	0.107	7.87	54.85	25.47	19.85	1.38	50.48	36.16
10.02	0.122	7.62	62.47	28.77	22.32	1.55	57.57	
10.05	0.138	7.54	70.01	32.11	24.89	1.71	63.66	45.34
10.08	0.153	7.69	77.70	35.18	27.29	1.88	69.10	
10.12	0.168	7.82	85.52	38.20	29.69	2.04	75.18	54.92
10.15	0.183	7.80	93.32	42.38	33.13	2.20	81.52	
10.18	0.199	7.82	101.14	45.24	35.44	2.36	87.88	65.62
10.22	0.214	7.87	109.01	48.05	37.76	2.53	94.39	
10.25	0.229	7.75	116.76	50.64	39.97	2.68	100.22	75.08
10.28	0.245	7.63	124.39	53.30	42.15	2.84	105.76	
10.32	0.260	7.58	131.97	56.46	44.67	2.94	111.83	84.30
10.35	0.275	7.62	139.59	59.64	47.20	3.05	118.15	
10.38	0.290	7.72	147.31	62.86	49.77	3.16	124.51	93.59
10.42	0.306	7.73	155.04	66.09	52.34	3.27	130.95	
10.45	0.321	7.63	162.67	69.27	54.88	3.38	137.40	102.90
10.48	0.336	7.66	170.33	71.49	56.81	3.53	143.71	
10.52	0.352	7.74	178.07	74.78	59.60	3.67	149.88	112.23
10.55	0.367	7.74	185.81	77.55	61.84	3.82	155.79	116.92
		Rate (g/s) ->		26.93	21.47	1.33	54.09	40.66

Constable Street Project

Sewage Pollutant Data : 17.05.95a

No.	Time Hrs	Time Mins	Time Dec.	Flow V (m/s)	Flow D (m)	Flow Q (m^3/s)	Bot Tube TSS (mg/l)	Bot Tube VSS (mg/l)	Bot Tube Vol (%)	Bot Tube Ammonia (mg/l)	Bot Tube COD (mg/l)	Bot Tube BOD (mg/l)	Top Tube TSS (mg/l)	Top Tube VSS (mg/l)	Top Tube Vol (%)	Top Tube Ammonia (mg/l)	Top Tube COD (mg/l)	Top Tube BOD (mg/l)
1	2	48	2.800	0.138	0.456	0.030	53	59	100.0	10.7	195	110	44	37	84.1	11.0	183	85
2	2	53	2.883	0.128	0.456	0.028	71	73	100.0	10.7	303		64	54	84.4	10.1	237	
3	2	58	2.967	0.123	0.455	0.026	60	63	100.0	9.4	196	110	58	44	75.9	10.6	184	118
4	3	3	3.050	0.120	0.457	0.026	53	56	100.0	9.8	187		51	39	76.5	9.0	198	
5	3	8	3.133	0.132	0.456	0.028	52	48	92.3	9.8	194	61	44	23	52.3	9.0	202	134
6	3	13	3.217	0.122	0.454	0.026	44	29	65.9	9.0	194		40	19	47.5	9.0	97	
7	3	18	3.300	0.128	0.454	0.027	37	32	86.5	8.7	209	61	41	35	85.4	9.0	143	37
8	3	23	3.383	0.118	0.455	0.025	35	40	100.0	8.7	155		35	34	97.1	8.6	162	
9	3	28	3.467	0.120	0.454	0.026	35	42	100.0	8.0	171	53	39	31	79.5	8.2	139	29
10	3	33	3.550	0.122	0.455	0.026	34	39	100.0	8.0	159		42	33	78.6	7.9	240	
11	3	38	3.633	0.120	0.452	0.026	29	31	100.0	7.7	195	53	31	26	83.9	7.6	121	37
12	3	43	3.717	0.120	0.454	0.026	27	24	88.9	7.4	198		39	29	74.4	7.3	267	
13	3	48	3.800	0.115	0.453	0.025	24	39	100.0	7.7	186	53	43	45	100.0	7.6	148	69
14	3	53	3.883	0.117	0.454	0.025	34	42	100.0	7.4	182		37	38	100.0	7.6	100	
15	3	58	3.967	0.123	0.453	0.026	40	35	87.5	7.4	208	69	38	40	100.0	7.3	184	102
16	4	3	4.050	0.118	0.453	0.025	36	41	100.0	7.4	301		37	37	100.0	7.3	191	
17	4	8	4.133	0.115	0.454	0.025	117	36	30.8	7.4	180	37	33	35	100.0	7.3	125	45
18	4	13	4.217	0.123	0.454	0.026	28	33	100.0	7.4	233		33	36	100.0	7.3	178	
19	4	18	4.300	0.128	0.455	0.027	31	38	100.0	7.1	165	53	33	39	100.0	7.0	230	53
20	4	23	4.383	0.128	0.455	0.027	76	30	39.5	6.8	150		38	43	100.0	6.7	319	
21	4	28	4.467	0.137	0.455	0.029	32	37	100.0	7.1	199	45	38	45	100.0	7.9	112	61
22	4	33	4.550	0.135	0.456	0.029	35	39	100.0	7.1	193		34	44	100.0	7.6	283	
23	4	38	4.633	0.135	0.456	0.029	29	32	100.0	6.8	164	53	34	40	100.0	6.7	273	85
24	4	43	4.717	0.143	0.456	0.031	30	36	100.0	6.5	161		28	33	100.0	6.7	263	
	Averages ->			0.125	0.455	0.027	43	41	91.3	8.1	195	63.2	40	37	88.3	9.2	266	71.3

Cumulative Transport Rates

Bed-Load Dry wt

0.312 kg

Tot B-L : Tot SS

0.037

Tot B-L / Tot Solids

3.613 %

B-L Conc

1.6 mg/l

Time	B-L (kg)	Q	Q (m^3)	Bottom Tube TSS (kg)	Bottom Tube VSS (kg)	Bottom Tube Ammonia (kg)	Bottom Tube COD (kg)	Bottom Tube BOD (kg)	Top Tube TSS (kg)	Top Tube VSS (kg)	Top Tube Ammonia (kg)	Top Tube COD (kg)	Top Tube BOD (kg)
2.80	0.013	8.55	8.55	0.45	0.50	0.09	1.67	0.94	0.38	0.32	0.09	1.56	0.73
2.88	0.026	8.05	16.60	1.02	1.09	0.18	3.60		0.89	0.75	0.18	3.29	
2.97	0.039	7.78	24.37	1.49	1.58	0.25	5.80	2.67	1.34	1.09	0.26	4.95	2.59
3.05	0.052	8.05	32.43	1.92	2.03	0.33	7.29		1.75	1.41	0.33	6.46	
3.13	0.065	8.08	40.50	2.34	2.42	0.41	8.83	3.66	2.11	1.59	0.40	7.79	4.75
3.22	0.078	7.95	48.45	2.69	2.65	0.48	10.39		2.43	1.74	0.47	8.98	
3.30	0.091	7.85	56.30	2.98	2.90	0.55	12.00	4.63	2.75	2.02	0.54	10.05	5.33
3.38	0.104	7.60	63.90	3.24	3.21	0.61	13.42		3.01	2.28	0.61	11.21	
3.47	0.117	7.70	71.60	3.51	3.53	0.68	14.66	5.44	3.31	2.52	0.67	12.58	5.78
3.55	0.130	7.70	79.30	3.78	3.83	0.74	15.93		3.64	2.77	0.73	13.86	
3.63	0.143	7.65	86.95	4.00	4.07	0.80	17.30	6.25	3.87	2.97	0.79	15.48	6.34
3.72	0.156	7.50	94.45	4.20	4.25	0.85	18.80		4.17	3.19	0.85	16.84	
3.80	0.169	7.40	101.85	4.38	4.54	0.91	20.24	7.04	4.49	3.52	0.90	18.13	7.38
3.88	0.182	7.65	109.50	4.64	4.86	0.96	21.60		4.77	3.81	0.96	19.20	
3.97	0.195	7.70	117.20	4.95	5.13	1.02	23.09	8.11	5.06	4.12	1.02	20.41	8.93
4.05	0.208	7.45	124.65	5.21	5.43	1.08	25.05		5.34	4.39	1.07	21.69	
4.13	0.221	7.60	132.25	6.10	5.71	1.13	26.84	8.66	5.59	4.66	1.13	22.92	9.61
4.22	0.234	8.00	140.25	6.33	5.97	1.19	28.41		5.85	4.95	1.18	24.27	
4.30	0.247	8.15	148.40	6.58	6.28	1.25	30.01	9.52	6.12	5.27	1.24	26.21	10.47
4.38	0.260	8.48	156.88	7.22	6.53	1.31	31.29		6.44	5.63	1.30	28.00	
4.47	0.273	8.73	165.60	7.50	6.86	1.37	32.77	10.30	6.77	6.02	1.37	30.02	11.52
4.55	0.286	8.65	174.25	7.81	7.19	1.43	34.48		7.07	6.40	1.43	31.96	
4.63	0.299	8.93	183.18	8.06	7.48	1.49	36.02	11.69	7.37	6.76	1.49	34.32	13.76
4.72	0.312	8.60	191.78	8.32	7.79	1.54	37.47	12.15	7.61	7.04	1.55	36.71	14.49
	Rate (g/s) ->			1.16	1.08	0.21	5.20	1.69	1.06	0.98	0.22	5.10	1.99

Sewage Pollutant Data : 17.05.95b

No.	Time Hrs	Time Mins	Time Dec.	Flow V (m/s)	Flow D (m)	Flow Q (m^3/s)	Bot Tube TSS (mg/l)	Bot Tube VSS (mg/l)	Bot Tube Vol (%)	Bot Tube Ammonia (mg/l)	Bot Tube COD (mg/l)	Bot Tube BOD (mg/l)	Top Tube TSS (mg/l)	Top Tube VSS (mg/l)	Top Tube Vol (%)	Top Tube Ammonia (mg/l)	Top Tube COD (mg/l)	Top Tube BOD (mg/l)
1	5	45	5.750	0.153	0.467	0.033	36	32	88.9	8.3	133	52	26	28	100.0	8.7	252	18
2	5	47	5.783	0.154	0.468	0.033	31	27	87.1	8.7	127		25	26	100.0	8.0	165	
3	5	49	5.817	0.155	0.468	0.033	28	24	85.7	8.0	151	40	31	28	90.3	7.7	260	29
4	5	51	5.850	0.156	0.469	0.034	30	22	73.3	8.7	184		32	28	87.5	8.0	236	
5	5	53	5.883	0.158	0.469	0.034	31	15	48.4	9.0	269	74	30	24	80.0	8.3	212	29
6	5	55	5.917	0.159	0.470	0.034	31	10	32.3	9.0	162		31	20	64.5	8.7	265	
7	5	57	5.950	0.160	0.470	0.034	36	36	100.0	9.4	290	29	31	36	100.0	9.0	378	40
8	5	59	5.983	0.161	0.471	0.035	37	41	100.0	9.0	284		32	37	100.0	9.0	380	
9	6	1	6.017	0.162	0.471	0.035	47	45	95.7	9.4	353	85	39	43	100.0	9.0	227	40
10	6	3	6.050	0.163	0.472	0.035	48	46	95.8	9.0	192		39	42	100.0	9.0	237	
11	6	5	6.083	0.165	0.472	0.036	46	40	87.0	9.0	348	40	38	37	97.4	9.0	305	244
12	6	7	6.117	0.166	0.472	0.036	42	37	88.1	9.4	176		47	41	87.2	9.0	181	
13	6	9	6.150	0.166	0.472	0.036	51	53	100.0	9.0	209	29	38	42	100.0	9.0	223	18
14	6	11	6.183	0.168	0.471	0.037	38	44	100.0	9.0	304		41	43	100.0	9.0	360	
15	6	13	6.217	0.168	0.472	0.038	42	50	100.0	9.0	278	40	41	43	100.0	9.4	179	29
16	6	15	6.250	0.172	0.471	0.038	45	54	100.0	9.4	212		41	48	100.0	9.4	334	
17	6	17	6.283	0.170	0.473	0.038	53	59	100.0	9.8	298	29	43	50	100.0	10.2	203	40
18	6	19	6.317	0.173	0.475	0.039	47	54	100.0	10.2	218		46	53	100.0	9.8	354	
19	6	21	6.350	0.172	0.475	0.038	51	61	100.0	10.2	251	97	45	53	100.0	10.2	322	18
20	6	23	6.383	0.177	0.476	0.039	56	63	100.0	10.2	237		35	42	100.0	10.2	285	
21	6	25	6.417	0.177	0.476	0.039	59	68	100.0	10.2	265	63	56	60	100.0	10.2	242	74
22	6	27	6.450	0.178	0.477	0.040	60	65	100.0	9.8	282		53	63	100.0	10.2	251	
23	6	29	6.483	0.175	0.477	0.039	59	65	100.0	10.2	247	85	59	65	100.0	10.2	268	74
24	6	31	6.517	0.185	0.476	0.041	61	66	100.0	9.8	426		55	64	100.0	10.2	274	
	Averages ->			0.166	0.472	0.036	44	45	90.9	9.3	246	55.3	40	42	96.1	9.2	266.4	54.3

Cumulative Transport Rates

Bed-Load Dry wt

0.405 kg

Tot B-L : Tot SS

0.086

Tot B-L / Tot Solids

7.895 %

B-L Conc

3.9 mg/l

Time	B-L (kg)	Q (m^3/2 min)	Q (m^3)	Bottom Tube TSS (kg)	Bottom Tube VSS (kg)	Bottom Tube Ammonia (kg)	Bottom Tube COD (kg)	Bottom Tube BOD (kg)	Top Tube TSS (kg)	Top Tube VSS (kg)	Top Tube Ammonia (kg)	Top Tube COD (kg)	Top Tube BOD (kg)
5.75	0.017	3.96	3.96	0.14	0.13	0.03	0.53	0.20	0.10	0.11	0.03	1.00	0.07
5.78	0.034	3.99	7.94	0.27	0.23	0.07	1.04		0.20	0.21	0.07	1.89	
5.82	0.051	4.02	11.96	0.38	0.33	0.10	1.59	0.53	0.33	0.33	0.10	2.77	0.30
5.85	0.067	4.05	16.01	0.50	0.42	0.13	2.27		0.46	0.44	0.13	3.72	
5.88	0.084	4.08	20.10	0.63	0.48	0.17	3.19	1.13	0.58	0.54	0.16	4.68	0.54
5.92	0.101	4.12	24.22	0.75	0.52	0.21	4.07		0.71	0.62	0.20	5.84	
5.95	0.118	4.15	28.36	0.90	0.67	0.25	5.00	1.37	0.84	0.77	0.24	7.25	0.87
5.98	0.135	4.18	32.55	1.06	0.84	0.29	6.19		0.97	0.92	0.27	8.61	
6.02	0.152	4.21	36.76	1.26	1.03	0.33	7.52	2.08	1.13	1.11	0.31	9.79	1.21
6.05	0.169	4.25	41.00	1.46	1.23	0.36	8.67		1.30	1.28	0.35	10.87	
6.08	0.185	4.28	45.28	1.66	1.40	0.40	9.81	2.43	1.46	1.44	0.39	11.89	3.28
6.12	0.202	4.32	49.60	1.84	1.56	0.44	10.93		1.66	1.62	0.43	12.90	
6.15	0.219	4.41	54.01	2.06	1.79	0.48	11.76	2.68	1.83	1.80	0.47	14.00	3.44
6.18	0.236	4.49	58.50	2.23	1.99	0.52	12.90		2.02	2.00	0.51	15.12	
6.22	0.253	4.54	63.04	2.42	2.22	0.56	14.20	3.04	2.20	2.19	0.55	16.43	3.70
6.25	0.270	4.56	67.60	2.63	2.46	0.61	15.31		2.39	2.41	0.59	17.51	
6.28	0.287	4.59	72.19	2.87	2.73	0.65	16.48	3.31	2.59	2.64	0.64	18.86	4.06
6.32	0.304	4.62	76.81	3.09	2.98	0.70	17.66		2.80	2.89	0.69	20.21	
6.35	0.320	4.66	81.47	3.33	3.27	0.75	18.74	4.20	3.01	3.13	0.73	21.69	4.23
6.38	0.337	4.72	86.19	3.59	3.57	0.80	19.88		3.17	3.33	0.78	23.01	
6.42	0.354	4.74	90.93	3.87	3.89	0.84	21.07	4.80	3.44	3.62	0.83	24.23	4.93
6.45	0.371	4.72	95.65	4.15	4.19	0.89	22.36		3.69	3.91	0.88	25.43	
6.48	0.388	4.80	100.45	4.44	4.51	0.94	23.61	6.01	3.97	4.23	0.93	26.68	5.98
6.52	0.405	4.64	105.09	4.72	4.81	0.98	25.23	6.40	4.23	4.52	0.98	27.97	6.32
	Rate (g/s) ->			1.64	1.67	0.34	9.14	2.09	1.47	1.57	0.34	9.71	2.17

Constable Street Project

Sewage Pollutant Data : 13.06.95a

No.	Time Hrs	Time Mins	Time Dec.	Flow V (m/s)	Flow D (m)	Flow Q (m^3/s)	Bot Tube TSS (mg/l)	Bot Tube VSS (mg/l)	Bot Tube Vol (%)	Bot Tube Ammonia (mg/l)	Bot Tube COD (mg/l)	Bot Tube BOD (mg/l)	Top Tube TSS (mg/l)	Top Tube VSS (mg/l)	Top Tube Vol (%)	Top Tube Ammonia (mg/l)	Top Tube COD (mg/l)	Top Tube BOD (mg/l)
1	14	24	14.40	0.217	0.521	0.052	221	190	86.0	27.84	635	430	270	237	87.8	26.3	559	260
2	14	26	14.43	0.213	0.519	0.051	258	218	84.5	28.41	713		255	217	85.1	28.0	873	
3	14	28	14.47	0.220	0.514	0.052	225	189	84.0	29.58	851	532	299	254	84.9	27.4	945	509
4	14	30	14.50	0.225	0.515	0.053	304	235	77.3	28.99	956		315	244	77.5	27.4	904	
5	14	32	14.53	0.223	0.513	0.053	379	266	70.2	29.58	1001	532	418	306	73.2	27.4	877	520
6	14	34	14.57	0.232	0.506	0.054	411	268	65.2	28.41	853		341	189	55.4	26.9	773	
7	14	36	14.60	0.237	0.501	0.055	411	253	61.6	28.99	701	475	410	293	71.5	26.3	749	464
8	14	38	14.63	0.242	0.502	0.056	454	288	63.4	27.84	626		415	263	63.4	25.3	804	
9	14	40	14.67	0.235	0.502	0.054	400	235	58.8	27.84	676	441	428	276	64.5	24.7	701	520
10	14	42	14.70	0.232	0.509	0.054	424	259	61.1	26.20	614		364	224	61.5	25.3	743	
11	14	44	14.73	0.232	0.509	0.054	329	198	60.2	27.84	844	385	370	212	57.3	25.3	811	407
12	14	46	14.77	0.228	0.505	0.053	355	181	51.0	27.28	630		400	230	57.5	25.3	671	
13	14	48	14.80	0.230	0.503	0.054	337	225	66.9	27.96	748	473	369	209	56.6	24.7	648	520
14	14	50	14.83	0.228	0.505	0.054	337	225	66.9	27.96	748		371	217	58.5	25.3	647	
15	14	52	14.87	0.232	0.507	0.054	337	225	66.9	27.96	748	473	333	204	61.3	25.8	1262	464
16	14	54	14.90	0.228	0.505	0.054	337	225	66.9	27.96	748		307	241	78.5	29.0	582	
17	14	56	14.93	0.225	0.501	0.052	337	225	66.9	27.96	748	473	255	126	49.4	29.0	637	430
18	14	58	14.97	0.237	0.499	0.055	194	127	65.5	26.31	710		372	297	79.8	29.0	619	
19	15	0	15.00	0.242	0.502	0.056	347	246	70.9	26.31	665	520	228	158	69.3	27.8	646	407
20	15	2	15.03	0.235	0.506	0.055	337	225	66.9	27.96	748		295	204	69.2	29.0	555	
21	15	4	15.07	0.230	0.503	0.054	337	225	66.9	27.96	748	473	253	179	70.8	27.8	570	486
22	15	6	15.10	0.225	0.498	0.052	337	225	66.9	27.96	748		253	187	73.9	29.6	893	
23	15	8	15.13	0.225	0.501	0.052	337	225	66.9	27.96	748	473	312	218	69.9	29.0	640	475
24	15	10	15.17	0.237	0.499	0.055	337	225	66.9	27.96	748		226	154	68.1	29.0	682	
	Averages ->			0.230	0.506	0.054	337	225	67.9	28.0	748	473.5	327	222	68.5	27	741	415.7

Cumulative Transport Rates

Bed-Load Dry wt

0.4643 kg

Tot B-L : Tot SS

0.009

Tot B-L / Tot Solids

0.882 %

B-L Conc

3.0 mg/l

Time	B-L (kg)	Q (m^3/2 min)	Q (m^3)	Bottom Tube TSS (kg)	Bottom Tube VSS (kg)	Bottom Tube Ammonia (kg)	Bottom Tube COD (kg)	Bottom Tube BOD (kg)	Top Tube TSS (kg)	Top Tube VSS (kg)	Top Tube Ammonia (kg)	Top Tube COD (kg)	Top Tube BOD (kg)
14.40	0.019	6.14	6.14	1.36	1.17	0.17	3.90	2.64	1.66	1.46	0.16	3.43	1.60
14.43	0.039	6.16	12.30	2.95	2.51	0.35	8.04		3.23	2.79	0.33	8.30	
14.47	0.058	6.32	18.62	4.37	3.70	0.53	12.85	9.27	5.12	4.40	0.51	13.89	7.95
14.50	0.077	6.37	24.99	6.30	5.20	0.72	18.56		7.12	5.95	0.68	19.63	
14.53	0.097	6.42	31.41	8.74	6.91	0.91	24.80	16.07	9.81	7.92	0.86	25.05	14.61
14.57	0.116	6.55	37.96	11.43	8.66	1.09	30.75		12.04	9.15	1.03	30.19	
14.60	0.135	6.66	44.62	14.17	10.35	1.29	35.84	22.35	14.77	11.11	1.21	35.26	20.73
14.63	0.155	6.63	51.25	17.18	12.26	1.47	40.26		17.52	12.85	1.38	40.27	
14.67	0.174	6.54	57.79	19.79	13.80	1.65	44.57	28.16	20.32	14.65	1.54	45.24	27.58
14.70	0.193	6.53	64.32	22.56	15.49	1.82	48.79		22.70	16.12	1.70	50.15	
14.73	0.213	6.46	70.78	24.69	16.77	2.00	53.55	33.16	25.09	17.49	1.87	55.00	32.88
14.77	0.232	6.42	77.20	26.97	17.93	2.18	58.31		27.66	18.96	2.03	59.58	
14.80	0.251	6.43	83.63	29.13	19.38	2.36	62.36	39.24	30.03	20.31	2.19	63.79	39.56
14.83	0.271	6.47	90.10	31.31	20.83	2.54	67.17		32.43	21.71	2.35	69.27	
14.87	0.290	6.47	96.57	33.49	22.29	2.72	72.01	45.37	34.59	23.03	2.52	74.64	45.56
14.90	0.310	6.35	102.92	35.62	23.72	2.90	76.85		36.54	24.56	2.70	79.99	
14.93	0.329	6.44	109.36	37.79	25.17	3.08	81.60	51.42	38.18	25.37	2.89	83.88	51.06
14.97	0.348	6.68	116.04	39.09	26.02	3.25	88.30		40.66	27.36	3.08	87.97	
15.00	0.368	6.68	122.72	41.40	27.66	3.43	90.89	58.38	42.19	28.41	3.27	92.02	56.50
15.03	0.387	6.51	129.23	43.60	29.13	3.61	95.33		44.11	29.74	3.46	95.96	
15.07	0.406	6.33	135.56	45.73	30.55	3.79	100.20	64.45	45.71	30.87	3.63	100.34	62.75
15.10	0.426	6.26	141.82	47.83	31.96	3.96	104.94		47.29	32.04	3.82	104.78	
15.13	0.445	6.44	148.26	50.00	33.41	4.14	109.62	70.47	49.30	33.45	4.00	109.40	68.78
15.17	0.464	6.52	154.78	52.20	34.88	4.33	114.44	76.62	50.77	34.45	4.19	113.83	75.77
		Rate (g/s) ->		18.12	12.11	1.50	39.74	25.53	17.63	11.96	1.46	39.52	24.92

Sewage Pollutant Data : 13.06.95b

No.	Time Hrs	Time Mins	Time Dec.	Flow V (m/s)	Flow D (m)	Flow Q (m^3/s)	Bot Tube TSS (mg/l)	Bot Tube VSS (mg/l)	Bot Tube Vol (%)	Bot Tube Ammonia (mg/l)	Bot Tube COD (mg/l)	Bot Tube BOD (mg/l)	Top Tube TSS (mg/l)	Top Tube VSS (mg/l)	Top Tube Vol (%)	Top Tube Ammonia (mg/l)	Top Tube COD (mg/l)	Top Tube BOD (mg/l)
1	15	50	15.83	0.240	0.509	0.057	248	189	76.1	28.7	581	348.0	226	189	83.6	26.7	568	
2	15	52	15.87	0.245	0.509	0.058	248	189	76.1	28.7	581		210	135	64.3	27.8	512	340
3	15	54	15.90	0.235	0.507	0.055	248	189	76.1	28.7	581	348.0	213	152	71.4	29.0	599	
4	15	56	15.93	0.242	0.505	0.057	248	189	76.1	28.7	581		230	155	67.4	29.0	492	351
5	15	58	15.97	0.247	0.503	0.058	258	202	78.3	29.7	544	348.0	228	141	61.8	27.8	590	
6	16	0	16.00	0.242	0.504	0.057	274	211	77.0	29.0	422		248	211	85.1	29.1	560	340
7	16	2	16.03	0.250	0.503	0.058	277	219	79.1	29.0	326	238	255	170	66.7	28.5	524	
8	16	4	16.07	0.247	0.503	0.057	199	146	73.4	29.0	534		279	213	76.3	28.5	584	407
9	16	6	16.10	0.247	0.505	0.058	232	182	78.4	29.0	719	204	266	156	58.6	28.5	510	
10	16	8	16.13	0.243	0.507	0.057	248	189	76.1	28.7	581	348.0	260	166	63.8	28.5	582	396
11	16	10	16.17	0.243	0.505	0.057	248	189	76.1	28.7	581		253	161	63.6	27.9	620	
12	16	12	16.20	0.243	0.501	0.057	248	189	76.1	28.7	581	348.0	253	146	57.7	28.5	646	453
13	16	14	16.23	0.235	0.499	0.055	248	189	76.1	28.7	581		281	224	79.7	28.5	553	
14	16	16	16.27	0.238	0.499	0.055	248	189	76.1	28.7	581	348.0	250	172	68.8	28.5	534	441
15	16	18	16.30	0.233	0.501	0.054	248	189	76.1	28.7	581		307	263	85.7	27.3	547	
16	16	20	16.33	0.240	0.502	0.056	270	210	77.8	27.8	698	453	268	214	79.9	27.9	656	430
17	16	22	16.37	0.237	0.501	0.055	242	184	76.0	27.8	578		280	211	75.4	27.9	613	
18	16	24	16.40	0.235	0.501	0.055	216	166	76.9	29.0	602	419	260	187	71.9	26.8	596	396
19	16	26	16.43	0.235	0.499	0.055	260	203	78.1	30.2	527		193	131	67.9	26.8	565	
20	16	28	16.47	0.233	0.500	0.054	235	178	75.7	30.2	601	385	279	215	77.1	27.3	600	396
21	16	30	16.50	0.225	0.500	0.052	277	209	75.5	29.0	685		320	248	77.5	28.5	566	
22	16	32	16.53	0.233	0.500	0.054	260	188	72.3	27.8	741	430	288	193	67.0	28.5	613	396
23	16	34	16.57	0.240	0.498	0.056	256	188	73.4	27.8	583		361	279	77.3	27.3	640	
24	16	36	16.60	0.230	0.500	0.054	268	206	76.9	29.0	411	272	313	231	73.8	27.3	693	407
25	16	38	16.63	0.233	0.500	0.054	248	189	76.1	29.0	600		266	178	66.9	28.5	728	
26	16	40	16.67	0.228	0.497	0.053	225	156	69.3	26.7	678	384.7	297	216	72.7	28.5	739	373
27	16	42	16.70	0.230	0.495	0.053	223	177	79.4	27.8	628		336	239	71.1	27.3	593	
	Averages ->			0.238	0.502	0.055	248	189	76.1	28.7	581	348.0	267	192	71.6	28.0	593.8	394.3

Cumulative Transport Rates

Bed-Load Dry wt

0.629 kg

Tot B-L : Tot SS

0.014

Tot B-L / Tot Solids

1.374 %

B-L Conc

3.5 mg/l

Time	B-L (kg)	Q (m^3/2 min)	Q (m^3)	Bottom Tube TSS (kg)	Bottom Tube VSS (kg)	Bottom Tube Ammonia (kg)	Bottom Tube COD (kg)	Bottom Tube BOD (kg)	Top Tube TSS (kg)	Top Tube VSS (kg)	Top Tube Ammonia (kg)	Top Tube COD (kg)	Top Tube BOD (kg)
15.83	0.023	6.86	6.86	1.70	1.30	0.20	3.99	2.39	1.55	1.30	0.18	3.90	
15.87	0.047	6.77	13.63	3.38	2.58	0.39	7.92		2.97	2.21	0.37	7.74	4.6
15.90	0.070	6.71	20.34	5.05	3.85	0.58	11.82	7.08	4.40	3.23	0.57	11.35	
15.93	0.093	6.86	27.20	6.75	5.14	0.78	15.80		5.98	4.29	0.76	15.11	9.4
15.97	0.116	6.85	34.05	8.52	6.53	0.98	19.54	11.85	7.54	5.26	0.95	18.87	
16.00	0.140	6.89	40.94	10.41	7.98	1.18	22.84		9.25	6.71	1.15	22.69	14.1
16.03	0.163	6.94	47.88	12.33	9.50	1.38	25.42	15.14	11.02	7.89	1.35	26.54	
16.07	0.186	6.90	54.78	13.70	10.51	1.58	28.40		12.94	9.36	1.55	30.31	19.7
16.10	0.210	6.88	61.66	15.30	11.76	1.78	32.73	17.95	14.77	10.44	1.74	34.19	
16.13	0.233	6.83	68.49	16.99	13.05	1.98	36.70	20.32	16.55	11.57	1.94	38.11	25.1
16.17	0.256	6.80	75.29	18.68	14.34	2.17	40.65		18.27	12.66	2.13	42.32	
16.20	0.280	6.67	81.96	20.34	15.60	2.36	44.52	25.01	19.96	13.64	2.32	46.44	31.2
16.23	0.303	6.60	88.56	21.98	16.85	2.55	48.36		21.81	15.12	2.51	50.30	
16.27	0.326	6.57	95.13	23.61	18.09	2.74	52.17	29.59	23.46	16.25	2.69	53.89	37.0
16.30	0.349	6.60	101.73	25.25	19.34	2.93	56.01		25.48	17.98	2.87	57.69	
16.33	0.373	6.66	108.39	27.04	20.73	3.12	60.23	35.59	27.27	19.41	3.06	61.69	42.7
16.37	0.396	6.59	114.98	28.64	21.95	3.30	64.48		29.11	20.80	3.24	65.83	
16.40	0.419	6.55	121.53	30.05	23.03	3.49	68.37	41.09	30.81	22.02	3.42	69.73	47.9
16.43	0.443	6.53	128.06	31.75	24.36	3.69	72.06		32.07	22.88	3.59	73.57	
16.47	0.466	6.40	134.46	33.26	25.50	3.88	75.75	46.07	33.86	24.25	3.77	77.34	53.0
16.50	0.489	6.38	140.84	35.02	26.83	4.06	79.86		35.90	25.84	3.95	81.14	
16.53	0.512	6.57	147.41	36.73	28.07	4.25	84.41	51.64	37.79	27.11	4.14	85.00	58.2
16.57	0.536	6.54	153.95	38.41	29.30	4.43	88.76		40.16	28.93	4.32	89.27	
16.60	0.559	6.45	160.40	40.13	30.63	4.61	92.01	55.17	42.17	30.42	4.49	93.61	63.5
16.63	0.582	6.46	166.86	41.74	31.85	4.80	95.27		43.89	31.57	4.68	97.93	
16.67	0.606	6.44	173.30	43.19	32.85	4.97	99.40	60.13	45.81	32.96	4.86	102.21	68.3
16.70	0.629	6.50	179.80	44.64	34.00	5.15	103.60	64.57	47.99	34.51	5.04	106.35	70.72
		Rate (g/s) ->		13.78	10.49	1.59	31.98	19.27	14.81	10.65	1.55	32.82	21.89

Constable Street Project

Sewage Pollutant Data : 20.06.95a

No.	Time Hrs	Time Mins	Time Dec.	Flow V (m/s)	Flow D (m)	Flow Q (m^3/s)	Bot Tube TSS (mg/l)	Bot Tube VSS (mg/l)	Bot Tube Vol (%)	Bot Tube Ammonia (mg/l)	Bot Tube COD (mg/l)	Bot Tube BOD (mg/l)	Top Tube TSS (mg/l)	Top Tube VSS (mg/l)	Top Tube Vol (%)	Top Tube Ammonia (mg/l)	Top Tube COD (mg/l)	Top Tube BOD (mg/l)
1	5	53	5.883	0.210	0.479	0.047	30	31	100.0	7.71	182	46	23	22	95.7	7.4	103	34
2	5	55	5.917	0.207	0.479	0.047	24	30	100.0	7.40	175		29	25	86.2	7.7	129	
3	5	57	5.950	0.210	0.478	0.047	50	53	100.0	8.03	197	68	36	33	91.7	7.7	130	46
4	5	59	5.983	0.202	0.479	0.045	29	41	100.0	8.71	205		44	36	81.8	8.2	145	
5	6	1	6.017	0.208	0.480	0.047	37	41	100.0	8.71	159	34	44	39	88.6	8.4	127	46
6	6	3	6.050	0.207	0.481	0.047	35	38	100.0	8.71	135		40	36	90.0	8.4	135	
7	6	5	6.083	0.203	0.481	0.046	35	36	100.0	8.71	165	23	39	32	82.1	8.4	175	12
8	6	7	6.117	0.207	0.482	0.047	57	54	94.7	9.07	149		27	29	100.0	8.8	113	
9	6	9	6.150	0.212	0.482	0.048	33	39	100.0	8.36	179	23	33	30	90.9	8.8	123	23
10	6	11	6.183	0.208	0.482	0.047	31	42	100.0	9.07	145		32	30	93.8	8.6	110	
11	6	13	6.217	0.210	0.483	0.048	23	32	100.0	8.71	122	12	28	28	100.0	8.4	125	12
12	6	15	6.250	0.212	0.484	0.048	22	32	100.0	9.07	122		30	25	83.3	8.4	147	
13	6	17	6.283	0.208	0.484	0.047	21	32	100.0	9.07	143	12	32	28	87.5	8.4	147	0
14	6	19	6.317	0.212	0.485	0.048	24	38	100.0	9.07	119		32	27	84.4	8.4	125	
15	6	21	6.350	0.213	0.485	0.049	28	30	100.0	9.07	129	57	38	32	84.2	8.4	112	36
16	6	23	6.383	0.215	0.485	0.049	36	44	100.0	9.84	135		34	30	88.2	9.1	142	
17	6	25	6.417	0.220	0.484	0.050	29	38	100.0	10.04	168	46	35	34	97.1	9.5	138	51
18	6	27	6.450	0.222	0.484	0.050	33	45	100.0	10.68	158		48	41	85.4	9.9	156	
19	6	29	6.483	0.222	0.486	0.050	35	41	99.8	10.98	159	57	56	54	96.4	10.1	150	57
20	6	31	6.517	0.220	0.486	0.050	35	41	99.8	11.28	159		47	41	87.2	10.1	160	
21	6	33	6.550	0.220	0.486	0.050	45	50	100.0	11.58	181	57	43	42	97.7	10.8	125	46
22	6	35	6.583	0.223	0.487	0.051	44	47	100.0	11.58	169		44	42	95.5	10.8	175	
23	6	37	6.617	0.227	0.488	0.052	50	51	100.0	12.57	163	79	46	42	91.3	10.8	155	46
24	6	39	6.650	0.232	0.491	0.053	54	66	100.0	12.07	192		45	39	86.7	10.8	159	
	Averages ->			0.214	0.483	0.048	35	41	99.8	9.6	159	42.8	38	34	90.2	9	138	34

Cumulative Transport Rates

Bed-Load Dry wt

0.244 kg

Tot B-L : Tot SS

0.050

Tot B-L / Tot Solids

4.753 %

B-L Conc

1.753 mg/l

Time	B-L (kg)	Q (m^3/2 min)	Q (m^3)	Bottom Tube TSS (kg)	Bottom Tube VSS (kg)	Bottom Tube Ammonia (kg)	Bottom Tube COD (kg)	Bottom Tube BOD (kg)	Top Tube TSS (kg)	Top Tube VSS (kg)	Top Tube Ammonia (kg)	Top Tube COD (kg)	Top Tube BOD (kg)
5.88	0.010	5.61	5.61	0.17	0.17	0.04	1.02	0.26	0.13	0.12	0.04	0.58	0.19
5.92	0.020	5.61	11.22	0.30	0.34	0.08	2.02		0.29	0.26	0.08	1.25	
5.95	0.031	5.54	16.76	0.58	0.64	0.13	3.07	1.02	0.49	0.45	0.13	2.01	0.70
5.98	0.041	5.54	22.30	0.74	0.86	0.18	4.18		0.73	0.65	0.17	2.75	
6.02	0.051	5.61	27.91	0.95	1.09	0.23	5.19	1.40	0.98	0.86	0.22	3.50	1.21
6.05	0.061	5.54	33.45	1.14	1.30	0.27	6.01		1.20	1.06	0.27	4.32	
6.08	0.071	5.55	39.00	1.33	1.50	0.32	6.84	1.65	1.42	1.24	0.31	5.10	1.34
6.12	0.081	5.67	44.67	1.66	1.81	0.37	7.71		1.57	1.41	0.36	5.86	
6.15	0.092	5.70	50.37	1.85	2.03	0.42	8.64	1.92	1.76	1.58	0.41	6.52	1.60
6.18	0.102	5.68	56.05	2.02	2.27	0.47	9.57		1.94	1.75	0.46	7.20	
6.22	0.112	5.72	61.77	2.15	2.45	0.52	10.33	2.05	2.10	1.91	0.51	7.92	1.73
6.25	0.122	5.69	67.46	2.28	2.64	0.57	11.02		2.27	2.05	0.56	8.72	
6.28	0.132	5.69	73.15	2.40	2.82	0.63	11.78	2.18	2.46	2.21	0.61	9.51	1.74
6.32	0.142	5.78	78.93	2.54	3.04	0.68	12.52		2.64	2.37	0.65	10.24	
6.35	0.153	5.84	84.77	2.70	3.21	0.73	13.24	2.84	2.86	2.55	0.70	10.97	2.15
6.38	0.163	5.91	90.68	2.91	3.47	0.79	14.01		3.06	2.73	0.76	11.74	
6.42	0.173	6.00	96.68	3.09	3.70	0.85	14.91	3.39	3.27	2.93	0.81	12.59	2.76
6.45	0.183	6.04	102.72	3.29	3.97	0.91	15.88		3.56	3.18	0.87	13.48	
6.48	0.193	6.02	108.74	3.50	4.22	0.98	16.84	4.07	3.90	3.51	0.93	14.42	3.44
6.52	0.203	6.00	114.74	3.71	4.47	1.05	17.80		4.18	3.75	1.00	15.29	
6.55	0.214	6.05	120.79	3.98	4.77	1.12	18.82	4.76	4.44	4.01	1.06	16.21	3.99
6.58	0.224	6.15	126.94	4.25	5.06	1.19	19.87		4.71	4.26	1.13	17.13	
6.62	0.234	6.27	133.21	4.56	5.38	1.27	20.90	5.75	5.00	4.53	1.19	18.13	4.56
6.65	0.244	6.07	139.28	4.89	5.78	1.34	22.01	6.22	5.27	4.76	1.26	19.08	8.83
		Rate (g/s) ->		1.70	2.01	0.47	7.64	2.08	1.83	1.65	0.44	6.62	1.65

Sewage Pollutant Data : 20.06.95b

No.	Time Hrs	Time Mins	Time Dec.	Flow V (m/s)	Flow D (m)	Flow Q (m^3/s)	Bot Tube TSS (mg/l)	Bot Tube VSS (mg/l)	Bot Tube Vol (%)	Bot Tube Ammonia (mg/l)	Bot Tube COD (mg/l)	Bot Tube BOD (mg/l)	Top Tube TSS (mg/l)	Top Tube VSS (mg/l)	Top Tube Vol (%)	Top Tube Ammonia (mg/l)	Top Tube COD (mg/l)	Top Tube BOD (mg/l)
1	7	36	7.600	0.279	0.522	0.067	196	166	84.1	22.7	492	272	174	136	78.2	25.9	559	375
2	7	38	7.633	0.281	0.523	0.067	170	122	71.8	22.7	509		159	124	78.0	26.8	483	
3	7	40	7.667	0.268	0.526	0.064	162	135	83.3	23.2	378	283	164	131	79.9	25.7	575	305
4	7	42	7.700	0.275	0.527	0.066	162	134	82.7	24.2	468		165	128	77.6	25.7	459	
5	7	44	7.733	0.270	0.526	0.065	178	148	83.1	23.7	548	407	190	152	80.0	25.7	465	294
6	7	46	7.767	0.277	0.522	0.068	190	160	84.2	23.7	532		191	156	81.7	25.7	474	
7	7	48	7.800	0.270	0.521	0.064	193	164	85.0	24.7	570	317	187	152	81.3	25.7	501	328
8	7	50	7.833	0.270	0.520	0.065	190	155	81.6	25.7	549		191	151	79.1	26.8	512	
9	7	52	7.867	0.263	0.518	0.063	188	158	84.0	26.8	578	328	197	159	80.7	26.8	547	362
10	7	54	7.900	0.273	0.518	0.065	191	162	84.8	27.4	570		200	168	84.0	26.8	552	
11	7	56	7.933	0.290	0.524	0.070	200	168	84.0	25.7	582	441	215	183	85.1	26.8	720	373
12	7	58	7.967	0.285	0.525	0.069	200	171	85.5	26.8	532		227	186	81.9	25.7	546	
13	8	0	8.000	0.283	0.525	0.068	201	169	84.1	26.8	601	418	240	197	82.1	26.3	540	385
14	8	2	8.033	0.277	0.524	0.066	192	161	83.9	26.3	663		197	163	82.7	26.8	561	
15	8	4	8.067	0.282	0.523	0.067	209	173	82.8	25.7	636	412	201	172	85.6	26.8	650	471
16	8	6	8.100	0.273	0.522	0.065	188	169	89.9	25.7	603		207	174	84.1	25.7	549	
17	8	8	8.133	0.263	0.522	0.063	263	234	89.0	25.7	483	465	199	169	84.9	25.7	513	452
18	8	10	8.167	0.267	0.519	0.064	202	167	82.7	24.7	568		192	165	85.9	24.7	574	
19	8	12	8.200	0.272	0.515	0.064	196	164	83.7	24.7	546	452	185	159	85.9	25.7	554	373
20	8	14	8.233	0.280	0.519	0.067	231	198	85.7	24.7	494		187	158	84.5	25.7	813	
21	8	16	8.267	0.273	0.524	0.065	218	185	84.9	24.7	533	509	210	175	83.3	25.7	548	407
22	8	18	8.300	0.268	0.524	0.064	226	195	86.3	26.3	565		219	188	85.8	25.7	556	
23	8	20	8.333	0.265	0.525	0.064	217	186	85.7	24.7	638	509	209	178	85.2	25.7	708	373
24	8	22	8.367	0.267	0.524	0.064	151	131	86.8	25.7	665		209	178	85.2	22.7	446	
	Averages ->			0.274	0.522	0.065	196	166	84.1	25.1	554	401.1	196	163	82.6	25.9	559	375.0

Cumulative Transport Rates

Bed-Load Dry wt

1.409 kg

Tot B-L : Tot SS

0.038

Tot B-L / Tot Solids

3.668 %

B-L Conc

7.477 mg/l

Time	B-L (kg)	Q (m^3/2 min)	Q (m^3)	Bottom Tube TSS (kg)	Bottom Tube VSS (kg)	Bottom Tube Ammonia (kg)	Bottom Tube COD (kg)	Bottom Tube BOD (kg)	Top Tube TSS (kg)	Top Tube VSS (kg)	Top Tube Ammonia (kg)	Top Tube COD (kg)	Top Tube BOD (kg)
7.60	0.059	8.06	8.06	1.58	1.33	0.18	3.96	2.19	1.40	1.10	0.21	4.50	3.02
7.63	0.117	7.90	15.96	2.93	2.30	0.36	8.00		2.66	2.08	0.42	8.84	
7.67	0.176	7.82	23.78	4.19	3.35	0.54	11.50	6.64	3.94	3.10	0.62	12.84	7.82
7.70	0.235	7.84	31.62	5.46	4.40	0.73	14.81		5.23	4.10	0.82	16.74	
7.73	0.294	7.84	39.46	6.86	5.56	0.92	18.79	13.02	6.72	5.30	1.03	20.40	12.44
7.77	0.352	7.82	47.28	8.34	6.82	1.10	23.02		8.22	6.52	1.23	24.16	
7.80	0.411	7.73	55.01	9.84	8.08	1.30	27.33	17.95	9.66	7.69	1.43	28.04	17.54
7.83	0.470	7.63	62.64	11.29	9.27	1.49	31.66		11.12	8.84	1.63	32.06	
7.87	0.528	7.66	70.30	12.73	10.48	1.70	35.96	22.96	12.63	10.06	1.84	36.15	23.07
7.90	0.587	8.07	78.37	14.27	11.78	1.92	40.35		14.24	11.42	2.05	40.80	
7.93	0.646	8.28	86.65	15.92	13.18	2.13	45.00	30.18	16.02	12.93	2.28	45.69	29.18
7.97	0.704	8.18	94.83	17.56	14.57	2.35	49.61		17.88	14.45	2.49	50.67	
8.00	0.763	8.04	102.87	19.18	15.93	2.57	54.25	36.96	19.81	16.04	2.70	55.16	35.42
8.03	0.822	8.01	110.88	20.71	17.22	2.78	59.33		21.39	17.34	2.91	59.86	
8.07	0.881	7.96	118.84	22.38	18.60	2.98	64.53	43.55	22.99	18.71	3.13	64.56	42.94
8.10	0.939	7.70	126.54	23.82	19.90	3.18	69.46		24.58	20.05	3.32	69.10	
8.13	0.998	7.60	134.14	25.82	21.68	3.38	73.64	50.66	26.09	21.34	3.52	73.30	49.86
8.17	1.057	7.68	141.82	27.37	22.96	3.57	77.64		27.57	22.60	3.71	77.45	
8.20	1.115	7.85	149.67	28.91	24.25	3.76	81.92	57.69	29.02	23.85	3.91	82.42	55.66
8.23	1.174	7.91	157.58	30.74	25.82	3.96	86.00		30.50	25.10	4.12	87.43	
8.27	1.233	7.77	165.35	32.43	27.25	4.15	90.06	65.67	32.13	26.46	4.32	92.49	62.05
8.30	1.291	7.66	173.01	34.17	28.75	4.35	94.33		33.81	27.90	4.51	97.18	
8.33	1.350	7.65	180.66	35.83	30.17	4.54	98.93	73.46	35.41	29.26	4.71	*******	67.76
8.37	1.409	7.77	188.43	37.00	31.19	4.74	103.92	74.03	37.03	30.64	4.89	*******	70.65
		Rate (g/s) ->		12.85	10.83	1.65	36.08	26.62	12.86	10.64	1.70	36.78	24.55

Constable Street Project

Sewage Pollutant Data : 17.07.95a

No.	Time Hrs	Time Mins	Dec.	Flow V (m/s)	Flow D (m)	Flow Q (m^3/s)	Bot Tube TSS (mg/l)	Bot Tube VSS (mg/l)	Bot Tube Vol (%)	Bot Tube Ammonia (mg/l)	Bot Tube COD (mg/l)	Bot Tube BOD (mg/l)	Top Tube TSS (mg/l)	Top Tube VSS (mg/l)	Top Tube Vol (%)	Top Tube Ammonia (mg/l)	Top Tube COD (mg/l)	Top Tube BOD (mg/l)
1	16	48	16.800	0.213	0.480	0.048	162	142	87.7	18.0	450		157	141	89.8	19.6	519	504
2	16	50	16.833	0.210	0.480	0.047	188	160	84.9	18.8	662	414	158	146	92.4	18.8	619	
3	16	52	16.867	0.207	0.482	0.047	184	161	87.1	18.8	746		179	162	90.5	18.4	609	425
4	16	54	16.900	0.208	0.481	0.047	208	182	87.5	18.0	605	425	168	154	91.7	18.0	570	
5	16	56	16.933	0.208	0.480	0.047	184	162	88.0	19.2	604		174	153	87.9	18.0	658	391
6	16	58	16.967	0.212	0.482	0.047	190	165	86.8	18.8	548	448	161	142	88.2	17.6	604	
7	17	0	17.000	0.212	0.483	0.048	194	174	89.7	18.0	607		167	147	88.0	17.3	585	414
8	17	2	17.033	0.213	0.483	0.048	184	161	87.1	19.1	621	441.5	159	140	88.1	16.6	578	
9	17	4	17.067	0.208	0.483	0.047	184	161	87.1	19.1	621		175	155	88.6	16.6	662	470
10	17	6	17.100	0.212	0.483	0.048	173	184	100.0	18.0	537	436	163	145	89.0	16.6	557	
11	17	8	17.133	0.215	0.481	0.049	190	141	74.2	19.6	753		176	157	89.2	16.9	639	414
12	17	10	17.167	0.215	0.481	0.048	207	185	89.4	21.3	573	436	180	163	90.6	16.6	667	
13	17	12	17.200	0.215	0.483	0.048	186	164	88.2	20.4	615		192	174	90.6	16.6	655	459
14	17	14	17.233	0.215	0.484	0.049	193	152	78.8	20.4	623	538	174	157	90.2	16.6	579	
15	17	16	17.267	0.218	0.483	0.049	193	173	89.6	20.0	616		173	152	87.9	15.9	605	459
16	17	18	17.300	0.217	0.482	0.049	175	153	87.4	18.8	664	425	171	150	87.7	15.9	677	
17	17	20	17.333	0.210	0.481	0.047	198	179	90.4	18.8	683		164	147	89.6	15.9	751	527
18	17	22	17.367	0.212	0.481	0.048	176	153	86.9	19.2	615	436	223	189	84.8	15.9	666	
19	17	24	17.400	0.208	0.481	0.047	184	161	87.1	19.1	621		177	163	92.1	16.2	612	493
20	17	26	17.433	0.213	0.482	0.048	167	146	87.4	19.6	722	448	163	147	90.2	16.6	531	
21	17	28	17.467	0.212	0.481	0.048	184	159	86.4	19.6	625		153	139	90.8	15.9	579	391
22	17	30	17.500	0.210	0.481	0.047	168	144	86.7	19.2	697	436	149	136	91.3	15.6	544	
23	17	32	17.533	0.202	0.481	0.045	169	145	85.8	18.4	506		165	147	89.1	14.6	609	402
24	17	34	17.567	0.205	0.481	0.046	180	156	86.7	18.0	595	414	151	139	92.1	14.9	571	
	Averages ->			0.211	0.482	0.048	184	161	87.1	19.1	621	441.5	170	152	89.6	16.7	610	445.8

Cumulative Transport Rates

Bed-Load Dry wt

0.146 kg

Tot B-L : Tot SS

0.006

Tot B-L / Tot Solids

0.577 %

B-L Conc

1.1 mg/l

Time	B-L (kg)	Q (m^3/2 min)	Q (m^3)	Bottom Tube TSS (kg)	Bottom Tube VSS (kg)	Bottom Tube Ammonia (kg)	Bottom Tube COD (kg)	Bottom Tube BOD (kg)	Top Tube TSS (kg)	Top Tube VSS (kg)	Top Tube Ammonia (kg)	Top Tube COD (kg)	Top Tube BOD (kg)
16.80	0.006	5.69	5.69	0.92	0.81	0.10	2.56		0.89	0.80	0.12	2.95	2.87
16.83	0.012	5.62	11.31	1.98	1.71	0.21	5.09	4.68	1.78	1.62	0.24	5.87	
16.87	0.018	5.59	16.90	3.01	2.61	0.31	8.79		2.78	2.53	0.35	9.33	7.63
16.90	0.024	5.60	22.50	4.18	3.63	0.41	12.97	9.44	3.72	3.39	0.46	12.74	
16.93	0.030	5.64	28.14	5.21	4.54	0.52	16.38		4.70	4.25	0.58	15.96	12.03
16.97	0.037	5.71	33.85	6.30	5.48	0.63	19.83	14.52	5.62	5.06	0.69	19.71	
17.00	0.043	5.77	39.62	7.42	6.49	0.73	22.99		6.59	5.91	0.80	23.20	16.78
17.03	0.049	5.74	45.36	8.47	7.41	0.84	26.47	19.60	7.50	6.72	0.91	26.56	
17.07	0.055	5.73	51.09	9.53	8.33	0.95	30.03		8.50	7.60	1.02	29.87	22.18
17.10	0.061	5.80	56.89	10.53	9.40	1.06	33.64	24.63	9.45	8.45	1.12	33.71	
17.13	0.067	5.81	62.70	11.64	10.22	1.17	36.76		10.47	9.36	1.23	36.94	26.98
17.17	0.073	5.80	68.50	12.84	11.29	1.29	41.13	29.70	11.51	10.30	1.33	40.65	
17.20	0.079	5.82	74.32	13.92	12.25	1.41	44.46		12.63	11.32	1.43	44.53	32.31
17.23	0.085	5.88	80.20	15.05	13.14	1.53	48.08	35.99	13.65	12.24	1.52	48.38	
17.27	0.091	5.89	86.09	16.19	14.16	1.65	51.75		14.67	13.13	1.62	51.79	37.72
17.30	0.098	5.76	91.85	17.20	15.04	1.76	55.29	40.95	15.66	14.00	1.70	55.28	
17.33	0.104	5.68	97.53	18.32	16.06	1.87	59.07		16.59	14.83	1.79	59.12	43.74
17.37	0.110	5.65	103.18	19.32	16.92	1.97	62.92	45.89	17.85	15.90	1.90	63.37	
17.40	0.116	5.67	108.85	20.36	17.83	2.08	66.41		18.85	16.83	2.01	67.14	49.32
17.43	0.122	5.73	114.58	21.32	18.67	2.19	69.97	50.99	19.79	17.67	2.12	70.65	
17.47	0.128	5.69	120.27	22.37	19.57	2.31	74.08		20.66	18.46	2.23	73.67	53.79
17.50	0.134	5.55	125.82	23.29	20.37	2.41	77.55	55.90	21.49	19.21	2.34	76.88	
17.53	0.140	5.49	131.31	24.22	21.17	2.51	81.37		22.39	20.02	2.44	79.87	58.23
17.57	0.146	5.62	136.93	25.23	22.05	2.61	84.22	60.50	23.24	20.80	2.55	83.30	60.84
		Rate (g/s) ->		8.76	7.66	0.91	29.24	21.01	8.07	7.22	0.88	28.92	21.10

Sewage Pollutant Data : 17.07.95b

No.	Time Hrs	Time Mins	Dec.	Flow V (m/s)	Flow D (m)	Flow Q (m^3/s)	Bot Tube TSS (mg/l)	Bot Tube VSS (mg/l)	Bot Tube Vol (%)	Bot Tube Ammonia (mg/l)	Bot Tube COD (mg/l)	Bot Tube BOD (mg/l)	Top Tube TSS (mg/l)	Top Tube VSS (mg/l)	Top Tube Vol (%)	Top Tube Ammonia (mg/l)	Top Tube COD (mg/l)	Top Tube BOD (mg/l)
1	18	1	18.017	0.205	0.481	0.046	187	168	89.8	26.3	480		153	142	92.8	21.3	576	
2	18	6	18.100	0.210	0.482	0.048	166	149	89.8	28.5	512	448	169	158	92.3	20.4	576	448
3	18	11	18.183	0.212	0.481	0.048	192	167	87.0	26.3	661		197	183	92.9	19.6	628	
4	18	16	18.267	0.225	0.483	0.051	204	181	88.7	25.2	676	515	188	172	91.5	19.6	609	504
5	18	21	18.350	0.207	0.482	0.047	197	178	90.4	25.2	739		226	211	93.4	21.3	683	
6	18	26	18.433	0.213	0.483	0.048	197	176	89.3	23.2	591	493	188	162	86.2	19.6	624	482
7	18	31	18.517	0.215	0.483	0.049	176	157	89.2	23.2	582		166	150	90.4	19.6	559	
8	18	36	18.600	0.217	0.484	0.049	204	186	91.2	22.2	557	515	186	163	87.6	19.6	646	538
9	18	41	18.683	0.215	0.483	0.049	185	159	85.9	21.3	592		183	157	85.8	18.8	519	
10	18	46	18.767	0.213	0.483	0.048	207	186	89.9	19.6	671	538	196	169	86.2	18.0	640	561
11	18	51	18.850	0.213	0.482	0.048	221	204	92.3	23.2	779		198	174	87.9	18.0	585	
12	18	56	18.933	0.205	0.481	0.046	185	168	90.8	22.2	529	470	180	141	78.3	17.3	589	538
13	19	0	19.000	0.202	0.480	0.045	178	161	90.4	22.2	580		175	132	75.4	16.6	602	
14	19	5	19.083	0.205	0.479	0.046	175	159	90.9	22.2	543	515	166	131	78.9	16.6	635	482
15	19	10	19.167	0.205	0.478	0.046	194	176	90.7	21.3	578		192	148	77.1	15.9	707	
16	19	15	19.250	0.195	0.477	0.044	198	180	90.9	20.4	553	538	198	152	76.8	14.6	646	493
17	19	20	19.333	0.192	0.476	0.043	173	155	89.6	22.2	496		155	121	78.1	15.2	484	
18	19	25	19.417	0.188	0.475	0.042	159	145	91.2	23.2	500	402	162	153	94.4	19.6	572	425
19	19	30	19.500	0.195	0.474	0.043	162	146	90.1	24.1	461		165	154	93.3	19.6	526	
20	19	35	19.583	0.192	0.474	0.043	182	161	88.5	25.2	573	391	174	163	93.7	19.6	618	436
21	19	40	19.667	0.192	0.474	0.042	186	166	89.2	25.2	589		170	162	95.3	19.6	593	
22	19	45	19.750	0.205	0.475	0.046	181	165	91.2	25.2	578	425	177	166	93.8	19.6	619	414
23	19	50	19.833	0.187	0.476	0.042	221	200	90.5	26.3	547		186	176	94.6	18.8	553	
24	19	55	19.917	0.190	0.476	0.042	195	175	89.7	24.1	479	425	167	155	92.8	18.0	485	380
	Averages ->			0.204	0.479	0.046	189	170	89.9	23.7	577	473.1	180	158	87.9	18.8	594.8	475.0

Cumulative Transport Rates

Bed-Load Dry wt

0.439 kg

Tot B-L : Tot SS

0.007

Tot B-L / Tot Solids

0.701 %

B-L Conc

1.3 mg/l

Time	B-L (kg)	Q (m^3/5 min)	Q (m^3)	Bottom Tube TSS (kg)	Bottom Tube VSS (kg)	Bottom Tube Ammonia (kg)	Bottom Tube COD (kg)	Bottom Tube BOD (kg)	Top Tube TSS (kg)	Top Tube VSS (kg)	Top Tube Ammonia (kg)	Top Tube COD (kg)	Top Tube BOD (kg)
18.02	0.018	14.03	14.03	2.62	2.36	0.37	6.73		2.15	1.99	0.30	8.08	
18.10	0.037	14.25	28.28	4.99	4.48	0.77	13.57	12.66	4.55	4.21	0.60	16.29	12.66
18.18	0.055	14.73	43.00	7.82	6.94	1.16	21.11		7.45	6.91	0.90	24.77	
18.27	0.073	14.60	57.60	10.79	9.58	1.53	30.76	27.78	10.20	9.42	1.19	33.94	27.44
18.35	0.091	14.23	71.83	13.60	12.11	1.89	40.38		13.41	12.42	1.47	42.60	
18.43	0.110	14.53	86.35	16.48	14.67	2.22	51.11	41.95	16.15	14.77	1.78	52.52	41.29
18.52	0.128	14.68	101.03	19.04	16.97	2.56	59.78		18.58	16.98	2.06	61.68	
18.60	0.146	14.70	115.73	22.04	19.71	2.89	68.34	57.09	21.32	19.37	2.35	69.89	57.10
18.68	0.165	14.55	130.28	24.73	22.02	3.20	76.44		23.98	21.66	2.64	79.29	
18.77	0.183	14.45	144.73	27.72	24.71	3.48	85.00	72.69	26.81	24.10	2.91	86.79	73.36
18.85	0.201	14.13	158.85	30.84	27.59	3.81	94.48		29.61	26.56	3.16	95.83	
18.93	0.220	13.65	172.50	33.37	29.88	4.11	105.11	85.76	32.06	28.48	3.41	103.82	88.30
19.00	0.238	13.63	186.13	35.79	32.08	4.42	112.32		34.45	30.28	3.64	111.84	
19.08	0.256	13.78	199.90	38.20	34.27	4.72	120.31	99.88	36.74	32.08	3.87	120.14	101.50
19.17	0.274	13.45	213.35	40.81	36.63	5.01	127.61		39.32	34.07	4.09	128.68	
19.25	0.293	12.95	226.30	43.38	38.97	5.27	135.10	114.09	41.88	36.04	4.30	137.83	114.51
19.33	0.311	12.65	238.95	45.57	40.93	5.55	142.09		43.84	37.57	4.49	146.00	
19.42	0.329	12.73	251.68	47.59	42.77	5.85	148.40	124.30	45.90	39.52	4.68	152.16	125.30
19.50	0.348	12.85	264.53	49.67	44.65	6.16	154.83		48.02	41.50	4.93	159.51	
19.58	0.366	12.73	277.25	51.99	46.70	6.48	160.69	134.31	50.24	43.57	5.18	166.21	136.46
19.67	0.384	13.20	290.45	54.44	48.89	6.81	168.26		52.48	45.71	5.44	174.37	
19.75	0.403	13.08	303.53	56.81	51.04	7.14	175.96	145.48	54.80	47.88	5.69	182.12	147.33
19.83	0.421	12.58	316.10	59.59	53.56	7.47	183.23		57.14	50.10	5.94	189.90	
19.92	0.439	13.21	329.31	62.16	55.87	7.79	190.45	156.44	59.34	52.14	6.19	197.21	157.13
		Rate (g/s) ->		8.63	7.76	1.08	26.45	21.73	8.24	7.24	0.86	27.39	21.82

Constable Street Project

Sewage Pollutant Data : 26.07.95

No.	Time Hrs	Time Mins	Time Dec.	Flow V (m/s)	Flow D (m)	Flow Q (m^3/s)	Bot Tube TSS (mg/l)	Bot Tube VSS (mg/l)	Bot Tube Vol (%)	Bot Tube Ammonia (mg/l)	Bot Tube COD (mg/l)	Bot Tube BOD (mg/l)	Top Tube TSS (mg/l)	Top Tube VSS (mg/l)	Top Tube Vol (%)	Top Tube Ammonia (mg/l)	Top Tube COD (mg/l)	Top Tube BOD (mg/l)
1	22	3	22.050	0.208	0.480	0.047	163	129	79.1	25.2	393	362	154	138	89.6	19.0	428	373
2	22	8	22.133	0.205	0.480	0.046	188	146	77.7	22.3	546		170	145	85.3	19.8	470	
3	22	13	22.217	0.208	0.479	0.047	204	162	79.4	21.5	538	373	195	172	88.2	19.0	481	396
4	22	18	22.300	0.202	0.477	0.045	177	138	78.0	21.5	538		172	151	87.8	19.0	525	
5	22	23	22.383	0.197	0.479	0.044	185	141	76.2	21.5	500	407	162	139	85.8	19.0	494	429
6	22	28	22.467	0.202	0.477	0.045	219	161	73.5	22.3	533		144	127	88.2	19.8	505	
7	22	33	22.550	0.193	0.477	0.043	353	311	88.1	23.3	547	441	158	148	93.7	20.6	450	362
8	22	38	22.633	0.187	0.478	0.042	226	191	84.5	23.3	607		155	145	93.5	21.0	436	
9	22	43	22.717	0.193	0.476	0.043	155	133	85.8	22.3	396	316	133	123	92.5	20.6	393	328
10	22	48	22.800	0.197	0.475	0.044	161	139	86.3	23.3	371		147	133	90.5	20.6	396	
11	22	53	22.883	0.197	0.475	0.044	171	149	87.1	22.3	393	339	155	138	89.0	19.8	461	328
12	22	58	22.967	0.190	0.474	0.042	159	137	86.2	23.3	434		147	132	89.8	21.0	481	
13	23	3	23.050	0.187	0.473	0.041	161	152	94.4	23.3	411	373	146	131	89.7	21.0	502	339
14	23	8	23.133	0.185	0.474	0.041	156	138	88.5	22.3	398		141	136	96.5	20.6	415	
15	23	13	23.217	0.190	0.474	0.042	145	134	92.4	22.3	359	316	136	131	96.3	20.2	391	316
16	23	18	23.300	0.177	0.472	0.039	162	152	93.8	22.3	339		145	139	95.9	20.2	465	
17	23	23	23.383	0.178	0.472	0.039	241	227	93.9	23.1	452	358.5	127	121	95.3	21.0	410	316
18	23	28	23.467	0.180	0.471	0.040	203	185	91.3	23.1	452		126	121	96.0	21.0	409	
19	23	33	23.550	0.170	0.468	0.038	150	142	94.7	23.3	483	294	127	123	96.9	21.5	387	283
20	23	38	23.633	0.173	0.467	0.038	143	131	91.6	22.8	409		120	119	99.2	21.0	408	
21	23	43	23.717	0.177	0.467	0.039	132	107	81.1	23.7	400	350	127	122	96.1	21.9	394	316
22	23	48	23.800	0.188	0.466	0.041	158	147	93.0	24.7	391		145	140	96.6	22.8	400	
23	23	53	23.883	0.183	0.465	0.040	209	197	94.3	25.2	455	373	156	148	94.9	23.3	419	350
24	23	58	23.967	0.183	0.463	0.040	163	151	92.6	25.2	496		139	136	97.8	23.3	526	
	Averages ->			0.190	0.473	0.042	183	158	86.8	23.1	452	358.5	147	136	92.7	20.7	444	344.7

Cumulative Transport Rates

Bed-Load Dry wt

1.000 kg

Tot B-L : Tot SS

0.045

Tot B-L / Tot Solids

4.329 %

B-L Conc

8.3 mg/l

Time	B-L (kg)	Q (m^3/2 min)	Q (m^3)	Bottom Tube TSS (kg)	Bottom Tube VSS (kg)	Bottom Tube Ammonia (kg)	Bottom Tube COD (kg)	Bottom Tube BOD (kg)	Top Tube TSS (kg)	Top Tube VSS (kg)	Top Tube Ammonia (kg)	Top Tube COD (kg)	Top Tube BOD (kg)
22.05	0.042	5.56	5.56	0.91	0.72	0.14	2.19	2.01	0.86	0.77	0.11	2.38	2.07
22.13	0.083	5.56	11.12	1.95	1.53	0.26	5.22		1.80	1.57	0.22	4.99	
22.22	0.125	5.51	16.63	3.06	2.42	0.38	8.19	6.14	2.88	2.52	0.32	7.64	6.45
22.30	0.167	5.33	21.96	4.02	3.16	0.50	11.05		3.79	3.33	0.42	10.44	
22.38	0.208	5.33	27.29	5.01	3.91	0.61	13.72	10.47	4.66	4.07	0.52	13.07	11.03
22.47	0.250	5.28	32.57	6.16	4.76	0.73	16.53		5.42	4.74	0.63	15.74	
22.55	0.292	5.08	37.65	7.95	6.34	0.85	19.31	15.04	6.22	5.49	0.73	18.03	14.78
22.63	0.333	5.09	42.74	9.10	7.31	0.97	22.40		7.01	6.23	0.84	20.25	
22.72	0.375	5.22	47.96	9.91	8.01	1.08	24.47	18.30	7.70	6.87	0.95	22.30	18.15
22.80	0.417	5.26	53.22	10.76	8.74	1.20	26.42		8.48	7.57	1.05	24.38	
22.88	0.458	5.16	58.38	11.64	9.51	1.32	28.45	21.84	9.28	8.28	1.16	26.76	21.57
22.97	0.500	5.01	63.39	12.44	10.19	1.44	30.62		10.01	8.94	1.26	29.17	
23.05	0.542	4.93	68.32	13.23	10.94	1.55	32.65	25.54	10.73	9.59	1.37	31.64	24.94
23.13	0.583	4.97	73.29	14.01	11.63	1.66	34.63		11.43	10.26	1.47	33.71	
23.22	0.625	4.85	78.14	14.71	12.28	1.77	36.37	28.65	12.09	10.90	1.57	35.60	28.05
23.30	0.667	4.69	82.83	15.47	12.99	1.88	37.96		12.77	11.55	1.68	37.78	
23.38	0.708	4.73	87.56	16.61	14.06	1.98	40.09	32.03	13.37	12.12	1.76	39.72	31.03
23.47	0.750	4.62	92.18	17.55	14.92	2.09	42.18		13.95	12.68	1.86	41.61	
23.55	0.792	4.54	96.72	18.23	15.56	2.20	44.37	34.72	14.53	13.24	1.95	43.37	33.61
23.63	0.833	4.62	101.34	18.89	16.17	2.30	46.26		15.09	13.79	2.05	45.25	
23.72	0.875	4.80	106.14	19.53	16.68	2.42	48.18	38.02	15.70	14.38	2.16	47.15	36.59
23.80	0.917	4.87	111.01	20.30	17.40	2.54	50.09		16.40	15.06	2.27	49.09	
23.88	0.958	4.80	115.81	21.30	18.34	2.66	52.27	41.62	17.15	15.77	2.38	51.10	39.98
23.97	1.000	4.92	120.73	22.10	19.09	2.78	54.71	43.36	17.83	16.44	2.49	53.69	41.67
	Rate (g/s) ->			7.67	6.63	0.97	19.00	15.08	6.19	5.71	0.87	18.64	14.49

Sewage Pollutant Data : 27.07.95

No.	Time Hrs	Time Mins	Time Dec.	Flow V (m/s)	Flow D (m)	Flow Q (m^3/s)	Bot Tube TSS (mg/l)	Bot Tube VSS (mg/l)	Bot Tube Vol (%)	Bot Tube Ammonia (mg/l)	Bot Tube COD (mg/l)	Bot Tube BOD (mg/l)	Top Tube TSS (mg/l)	Top Tube VSS (mg/l)	Top Tube Vol (%)	Top Tube Ammonia (mg/l)	Top Tube COD (mg/l)	Top Tube BOD (mg/l)
1	0	29	0.483	0.152	0.454	0.032	139	131	94.2	20.6	324	283	130	115	88.5	22.3	430	283
2	0	34	0.567	0.140	0.453	0.030	118	114	96.6	20.2	327		116	106	91.4	22.3	399	
3	0	39	0.650	0.147	0.452	0.031	105	102	97.1	19.4	426	305	113	109	96.5	22.3	442	305
4	0	44	0.733	0.150	0.451	0.032	102	101	99.0	20.1	361		103	95	92.2	21.9	432	
5	0	49	0.817	0.165	0.452	0.035	158	154	97.8	17.8	378	242	97	96	99.0	21.9	397	294
6	0	54	0.900	0.162	0.450	0.034	111	108	97.3	19.8	354		92	92	100.0	21.5	400	
7	0	59	0.983	0.158	0.450	0.034	104	101	97.1	19.4	1850	339	92	90	97.8	21.0	420	237
8	1	4	1.067	0.173	0.451	0.037	107	98	91.6	19.4	297		93	90	96.8	20.2	464	
9	1	9	1.150	0.163	0.449	0.035	100	95	95.0	18.2	295	237	93	83	89.2	19.4	438	260
10	1	14	1.233	0.158	0.448	0.033	92	89	96.7	17.9	316		89	86	96.6	19.4	418	
11	1	19	1.317	0.150	0.449	0.032	99	90	90.9	18.2	402	226	88	84	95.5	18.2	375	215
12	1	24	1.400	0.145	0.447	0.031	186	183	98.5	17.8	378		90	93	100.0	19.4	413	
13	1	29	1.483	0.128	0.446	0.027	93	85	91.4	17.9	317	192	82	76	92.7	18.6	376	181
14	1	34	1.567	0.137	0.446	0.029	79	68	86.1	17.2	279		71	65	91.5	18.2	376	
15	1	39	1.650	0.128	0.444	0.027	80	71	88.8	17.5	255	192	70	67	95.7	18.2	372	192
16	1	44	1.733	0.142	0.445	0.030	79	69	87.3	24.7	236		64	61	95.3	17.5	339	
17	1	49	1.817	0.147	0.445	0.031	211	177	83.8	17.8	378	242	64	60	93.8	16.8	309	136
18	1	54	1.900	0.142	0.444	0.030	82	70	85.4	15.2	217		65	53	81.5	16.5	352	
19	1	59	1.983	0.155	0.443	0.033	62	49	80.0	17.8	378	242	73	63	86.3	16.5	312	170
20	2	4	2.067	0.152	0.442	0.032	89	74	83.1	14.9	240		72	62	86.1	16.1	381	
21	2	9	2.150	0.148	0.442	0.031	71	60	84.5	14.9	253	203	74	64	86.5	15.8	367	158
22	2	14	2.233	0.158	0.442	0.033	76	65	85.5	14.0	222		71	64	90.1	15.5	345	
23	2	19	2.317	0.158	0.441	0.033	66	59	89.4	13.7	349	203	72	64	88.9	14.9	354	158
24	2	24	2.400	0.152	0.441	0.032	59	56	94.9	13.2	230		73	68	93.2	14.3	282	
	Averages ->			0.150	0.447	0.032	103	95	91.3	17.8	378	242.3	85	79	92.7	18.7	383.0	215.6

Cumulative Transport Rates

Bed-Load Dry wt

1.000 kg

Tot B-L : Tot SS

0.107

Tot B-L / Tot Soilds

9.639 %

B-L Conc

11.0 mg/l

Time	B-L (kg)	Q (m^3/2 min)	Q (m^3)	Bottom Tube TSS (kg)	Bottom Tube VSS (kg)	Bottom Tube Ammonia (kg)	Bottom Tube COD (kg)	Bottom Tube BOD (kg)	Top Tube TSS (kg)	Top Tube VSS (kg)	Top Tube Ammonia (kg)	Top Tube COD (kg)	Top Tube BOD (kg)
0.48	0.042	3.71	3.71	0.52	0.49	0.08	1.20	1.05	0.48	0.43	0.08	1.60	1.05
0.57	0.083	3.63	7.34	0.94	0.90	0.15	2.39		0.90	0.81	0.16	3.04	
0.65	0.125	3.76	11.10	1.34	1.28	0.22	3.99	3.30	1.33	1.22	0.25	4.71	3.30
0.73	0.167	4.01	15.11	1.75	1.69	0.30	5.44		1.74	1.60	0.34	6.44	
0.82	0.208	4.17	19.28	2.41	2.33	0.38	7.01	5.28	2.15	2.00	0.43	8.09	5.71
0.90	0.250	4.08	23.36	2.86	2.77	0.46	8.46		2.52	2.38	0.51	9.73	
0.98	0.292	4.22	27.58	3.30	3.20	0.54	16.26	8.10	2.91	2.76	0.60	11.50	7.68
1.07	0.333	4.28	31.86	3.75	3.62	0.62	17.54		3.31	3.14	0.69	13.48	
1.15	0.375	4.08	35.94	4.16	4.01	0.70	18.74	10.08	3.69	3.48	0.77	15.27	9.85
1.23	0.417	3.89	39.83	4.52	4.35	0.77	19.97		4.03	3.82	0.84	16.90	
1.32	0.458	3.72	43.55	4.89	4.69	0.83	21.46	11.80	4.36	4.13	0.91	18.29	11.48
1.40	0.500	3.46	47.01	5.53	5.32	0.90	22.77		4.67	4.45	0.98	19.72	
1.48	0.542	3.36	50.37	5.84	5.60	0.96	23.83	13.11	4.95	4.71	1.04	20.98	12.72
1.57	0.583	3.36	53.73	6.11	5.83	1.01	24.77		5.19	4.92	1.10	22.25	
1.65	0.625	3.42	57.15	6.38	6.08	1.07	25.64	14.41	5.43	5.15	1.17	23.52	14.02
1.73	0.667	3.64	60.79	6.67	6.33	1.16	26.50		5.66	5.38	1.23	24.75	
1.82	0.708	3.64	64.43	7.44	6.97	1.23	27.88	16.18	5.89	5.59	1.29	25.88	15.00
1.90	0.750	3.74	68.17	7.75	7.23	1.29	28.69		6.13	5.79	1.35	27.19	
1.98	0.792	3.86	72.03	7.98	7.42	1.35	30.15	18.02	6.42	6.04	1.42	28.40	16.29
2.07	0.833	3.77	75.80	8.32	7.70	1.41	31.05		6.69	6.27	1.48	29.84	
2.15	0.875	3.85	79.65	8.59	7.93	1.47	32.02	19.57	6.97	6.52	1.54	31.25	17.50
2.23	0.917	3.97	83.62	8.89	8.19	1.52	32.91		7.25	6.77	1.60	32.62	
2.32	0.958	3.88	87.50	9.15	8.42	1.58	34.26	21.17	7.53	7.02	1.66	33.99	18.74
2.40	1.000	3.80	91.30	9.37	8.63	1.63	35.14	22.09	7.81	7.28	1.71	35.06	19.59
	Rate (g/s) ->			3.26	3.00	0.56	12.20	7.67	2.71	2.53	0.59	12.18	6.79

APPENDIX E : MULTI-DEPTH SUSPENDED SOLIDS DATA

28.06.95	Velocity (m/s)	Depth (m)	Flow (m^3/s)	Depth (mm)	TSS (mg/l)	VSS (mg/l)	Vol (%)	NH4 (mg/l)	COD (mg/l)	BOD (mg/l)
05-06	0.1444	0.4525	0.0308	0	56	45	80.7	8.4	213	276
				15	39	32	81.7	7.6	137	85
				30	29	24	83.2	7.9	147	55
				45	32	35	114.1	8.0	210	78
					TSS	VSS	Vol	NH4	COD	BOD
06-07	0.1889	0.4722	0.0419	0	82	68	82.6	15.6	458	119
				15	100	85	84.8	13.1	262	142
				30	79	67	84.9	13.0	238	146
				45	82	68	83.0	12.1	316	145
					TSS	VSS	Vol	NH4	COD	BOD
07-08	0.2436	0.5072	0.0572	0	406	364	86.7	22.5	606	262
				15	286	239	83.7	25.7	604	419
				30	241	199	82.8	23.9	655	326
				45	236	191	81.2	21.1	593	364
					TSS	VSS	Vol	NH4	COD	BOD
08-09	0.2547	0.5173	0.0606	0	605	509	84.2	32.5	1225	772
				15	473	393	83.3	31.1	811	794
				30	404	342	84.6	30.1	814	605
				45	414	343	82.6	26.0	947	609
					TSS	VSS	Vol	NH4	COD	BOD
AVG	0.2080	0.4873	0.0475	0	287	246	83.6	19.7	625	357
				15	224	187	83.4	19.4	454	360
				30	188	158	83.9	18.7	464	283
				45	191	159	90.2	16.8	516	299

10.07.95	Velocity (m/s)	Depth (m)	Flow (m^3/s)	Depth (mm)	TSS (mg/l)	VSS (mg/l)	Vol (%)	NH4 (mg/l)	COD (mg/l)	BOD (mg/l)
14-15	0.2547	0.4976	0.0589	0	497	395	81.6	29.4	828	577
				15	259	211	82.4	22.1	656	479
				30	230	181	78.6	23.2	672	644
				45	208	178	85.6	23.0	726	532
					TSS	VSS	Vol	NH4	COD	BOD
15-16	0.2492	0.4931	0.0573	0	251	214	84.8	28.8	726	431
				15	239	206	86.2	21.5	619	415
				30	221	187	84.9	22.6	784	546
				45	189	159	84.6	22.6	653	446
					TSS	VSS	Vol	NH4	COD	BOD
16-17	0.2578	0.4990	0.0598	0	343	242	74.2	29.4	649	449
				15	371	236	62.3	21.5	635	472
				30	318	212	72.1	22.7	748	584
				45	291	194	71.5	23.4	725	483
					TSS	VSS	Vol	NH4	COD	BOD
17-18	0.2686	0.4978	0.0622	0	306	244	80.2	26.6	649	464
				15	264	186	70.2	20.7	655	453
				30	273	207	77.9	21.8	679	565
				45	254	182	74.1	22.3	830	446
					TSS	VSS	Vol	NH4	COD	BOD
AVG	0.2575	0.4972	0.0595	0	347	271	79.9	28.4	697	464
				15	285	211	75.4	21.5	658	473
				30	260	197	78.4	22.6	721	585
				45	235	178	79.0	22.8	734	477

01.08.95	Velocity (m/s)	Depth (m)	Flow (m^3/s)	Depth (mm)	TSS (mg/l)	VSS (mg/l)	Vol (%)	NH4 (mg/l)	COD (mg/l)	BOD (mg/l)
06-07	0.105	0.436	0.022	0	42	42	99.7	23.0	151	313
				15	40	42	99.5	23.2	177	76
				30	43	43	96.7	22.1	143	226
				45	33	32	86.9	28.7	139	87
					TSS	VSS	Vol	NH4	COD	BOD
07-08	0.150	0.449	0.032	0	54	56	100.0	22.6	145	87
				15	56	49	90.7	22.6	164	132
				30	64	56	84.9	21.5	154	241
				45	56	49	89.6	28.6	170	102
					TSS	VSS	Vol	NH4	COD	BOD
08-09	0.215	0.479	0.048	0	210	196	93.9	23.4	405	277
				15	207	188	93.0	23.1	363	355
				30	177	159	90.8	21.5	384	336
				45	163	146	89.8	29.4	372	275
					TSS	VSS	Vol	NH4	COD	BOD
09-10	0.237	0.498	0.055	0	598	521	87.3	22.3	1166	695
				15	493	449	91.5	21.8	1127	878
				30	357	320	89.9	20.7	937	663
				45	357	312	87.5	26.9	821	543
					TSS	VSS	Vol	NH4	COD	BOD
AVG	0.177	0.466	0.039	0	226	204	95.2	22.8	467	343
				15	199	182	93.7	22.7	458	360
				30	157	142	90.8	21.5	405	372
				45	149	132	88.8	28.4	370	331

09.08.95	Velocity (m/s)	Depth (m)	Flow (m^3/s)	Depth (mm)	TSS (mg/l)	VSS (mg/l)	Vol (%)	NH4 (mg/l)	COD (mg/l)	BOD (mg/l)
06-07	0.1514	0.4526	0.0322	0	116	97	84.3	6.4	331	155
				15	99	86	90.9	5.9	325	106
				30	46	41	88.7	5.7	272	61
				45	36	36	97.3	6.0	131	57
					TSS	VSS	Vol	NH4	COD	BOD
07-08	0.1867	0.4668	0.0410	0	128	107	82.6	12.8	379	208
				15	97	91	94.2	10.5	357	140
				30	73	71	97.5	8.9	266	79
				45	64	61	96.1	8.1	163	68
					TSS	VSS	Vol	NH4	COD	BOD
08-09	0.2447	0.4979	0.0566	0	262	223	85.2	23.2	587	358
				15	248	219	88.8	18.5	706	411
				30	237	224	95.1	17.0	558	302
				45	195	182	93.0	15.9	395	260
					TSS	VSS	Vol	NH4	COD	BOD
09-10	0.2669	0.5107	0.0629	0	504	419	83.0	20.4	1023	765
				15	488	406	83.1	21.2	1024	607
				30	522	476	91.3	25.2	870	622
				45	409	367	89.7	25.4	785	558
					TSS	VSS	Vol	NH4	COD	BOD
AVG	0.2122	0.4825	0.0482	0	251	210	83.8	15.2	573	488
				15	229	197	89.5	13.6	594	305
				30	220	203	93.2	14.2	492	266
				45	176	162	94.0	13.9	368	236

APPENDIX F : DIMENSIONLESS GROUPS TESTED

This appendix details the dimensionless parameter groups employed in the analysis of the data collected at Study Site 3. The factors which the dimensionless groups are hypothesised as representing are also given. The groups were obtained from dimensional analysis, and from existing laboratory based studies (see Chapter 4).

Upstream Characteristics

$$\left(\frac{I_r TSSS}{D_r}\right) \quad \& \quad \left(\frac{I_r ADWP}{D_r}\right)$$

Particle Characteristics

$$\left(\frac{\rho_d}{\rho_w}\right), \left(\frac{\rho_s}{\rho_w}\right), \left(\frac{\hat{d}}{R}\right), \left(\frac{R}{\hat{d}}\right), \left(\frac{V_b^2}{gsy_o}\right), \left(\frac{V_b^2}{gsR}\right), \left(\frac{\lambda V_b^2}{gsD}\right), \left(\frac{V^2}{gsD}\right),$$

$$\left(\frac{\lambda V^2}{gs\hat{d}}\right), \left(\frac{\lambda V_b^2}{gs\hat{d}}\right), \left(D_{gr}\right), \left(\frac{V^2}{gsR}\right), \left(\frac{y}{\hat{d}}\right) \quad \& \quad \left(\frac{\lambda V^2}{gsD}\right)$$

Ambient Hydraulic Conditions

$$\left(\frac{\tau_o}{\tau_b}\right), \left(\frac{V_b^2}{gsy_o}\right), \left(\frac{D^2}{R}\right), \left(\frac{V_b^2}{gsR}\right), \left(\frac{\lambda V_b^2}{gsD}\right), \left(\frac{y}{D}\right), \left(\frac{D^2}{A}\right), \left(\frac{V^2}{gsD}\right),$$

$$\left(\frac{\lambda V^2}{gs\hat{d}}\right), \left(\frac{\lambda V_b^2}{gs\hat{d}}\right), \left(\frac{V^2}{gsR}\right), (\lambda), \ (Re) \quad \& \quad \left(\frac{\lambda V^2}{gsD}\right)$$

Inputs to the System

$$\left(\frac{Q}{Q_{max}}\right), \left(\frac{v}{v_{max}}\right), \left(\frac{y}{y_{max}}\right) \quad \& \quad C_v(TSS)$$

APPENDIX G : RHEOLOGICAL TESTING

Based on fundamental studies by Williams and Williams (1987), Kirby (1989), and Williams et al., (1989) and Wotherspoon (1994) assumed that sewer sediments can demonstrate elastico-viscous properties and that the steady shear methods used by geotechnical engineers to determine yield strength are not appropriate due to the heterogeneous nature of the material. Based on these assumptions Wotherspoon (1994) was able to select a method to test the yield strength of sediments using the direct shear stress and shear wave propagation techniques, via a cruciform vane geometry, and assumes a cylindrical failure surface, which causes the sample to fail via creep deformation.

A total of 61 tests were carried out, using a controlled stress rheometer. Samples were also tested for volumetric solids (V_s), moisture content (m), bulk density(ρ), voids ratio (e) and particle size distribution (d_{50}). In analysis of the data, linear and multiple regression of the data were undertaken in an attempt to determine if any of the measured physical parameters had an effect on yield strength. Based on this analysis the equations G.1, 2, 3, 4 and 5 were obtained.

$$\tau_y = 2.5728 \exp(10.9105 V_s) \quad (r^2 = 0.802) \quad \text{....G.1}$$

$$\tau_y = 1.71 \times 10^{-37} \rho^{12.2671} \quad (r^2 = 0.592) \quad \text{....G.2}$$

$$\tau_y = 9.66 \times 10^{7} m^{-3.1682} \quad (r^2 = 0.920) \quad \text{....G.3}$$

$$\tau_y = 6.37 \times 10^{2} e^{-2.5707} \quad (r^2 = 0.848) \quad \text{....G.4}$$

$$\tau_y = 3.86 \times 10^{-15} \rho_d^{5.6221} \quad (r^2 = 0.867) \quad \text{....G.5}$$

Wotherspoon (1994) found that of all the measured parameters moisture content provided the best correlation with yield strength, $r^2 = 0.920$, and this was proposed as the predictor relationship. The performance of this relationship is illustrated in Figure G.1. The researcher does recognise, however, that the degree of experimental error involved in determining the other physical characteristics (V_s, m, ρ and e) may be significant. This is mainly due to the small volumes of sample involved (typically ~50ml). It should also be noted at this stage that in calculating the moisture content the standard geotechnical method (BS 1377, 1975 and Craig, 1987) is used (equation 6) and in doing so it is possible to obtain moisture contents in excess of 100%.

$$m = \frac{M_w\text{, Mass of Water}}{M_s\text{, Mass of Solids}} \quad \text{....G.6}$$

Although moisture content clearly shows good correlation with the yield stress, it is difficult to believe that it is the sole parameter involved. Other parameters, such as density or organic content must be important, although moisture content must be related to these parameters. Bayer (1989), found that organic content was an important factor in the development of yield strength.

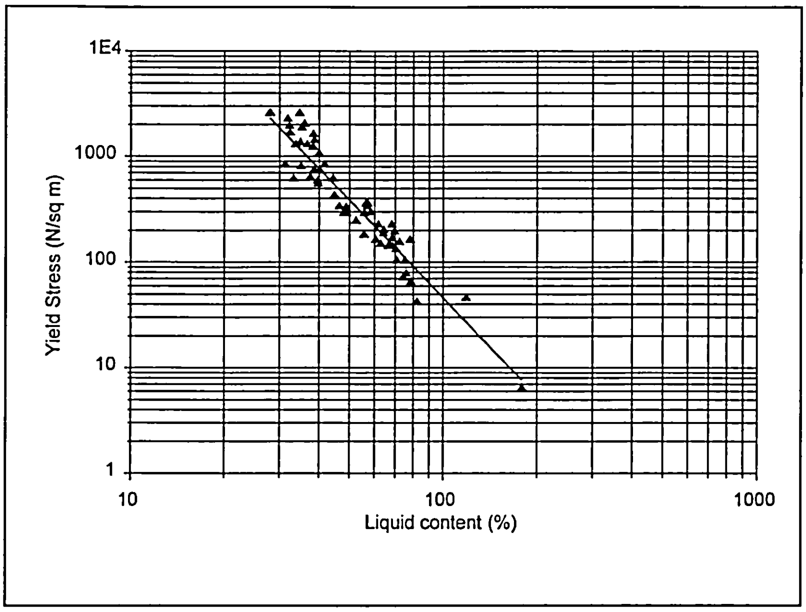

Figure G.1 : Data presented by Wotherspoon (1994)

In an attempt to resolve this question, a series of rheological tests were undertaken to confirm, or conceivably extend, the relationship obtained by Wotherspoon (1994). The tests undertaken were identical to those performed by Wotherspoon in all aspects except;

- A sample volume of ~150ml was used. This made the determination of the sediment characteristics (density etc.) more reliable. Additionally the larger containers required reduced the influence of any boundary effect between the sample and the container.
- An effort was made to obtain samples which were predominately made up of fine particles, thus larger particles would not have to be removed.

Obtaining samples from the field suitable for tested proved difficult due to the cleaning of the main interceptor sewer in Dundee. The samples which were obtained were highly organic and fine in nature. The fibrous nature of the organic fraction of the samples obtained made testing difficult in some cases. Additionally a major building exercise in the University campus at the time of testing made obtaining a constant room temperature in the laboratory difficult. When temperatures were high in the laboratory, sample strengths were observed to increase during testing as the samples reduced in moisture content. Despite these problems a total of 92 samples were tested.

The first stage in the data analysis was to compare the data obtained with the relationship obtained by Wotherspoon (1994), this is displayed graphically in Figure G.2. As the figure illustrated there are some data sets which conform quite well to the relationship obtained by Wotherspoon (1994), however the main bulk of the data does not.

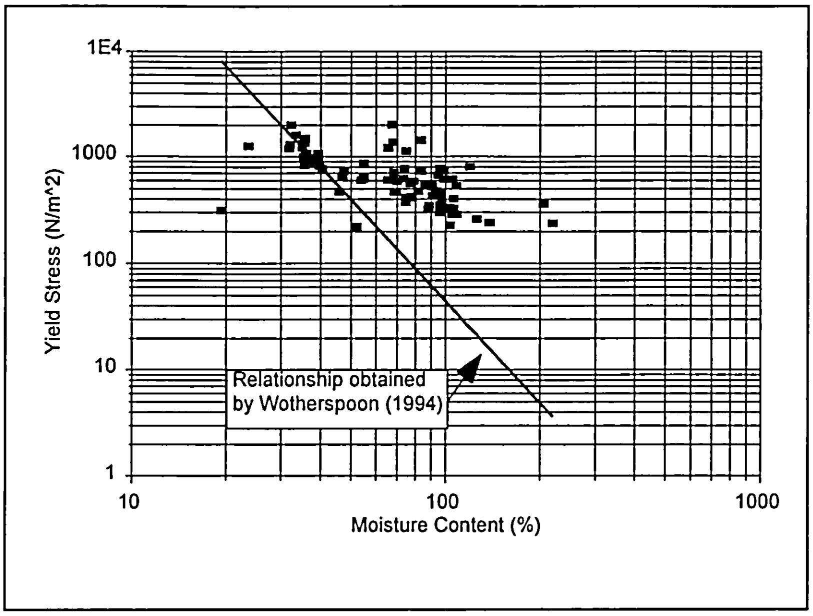

Figure G.2 : Data comparison.

Closer inspection of the data revealed that the samples with lower organic content, below 4%, conform better to the relationship obtained by Wotherspoon (1994). This is illustrated in Figure G.3. From the figure it can be seen that the majority of the data sets with organic levels below 4% conform reasonably well to the relationship obtained by Wotherspoon (1994).

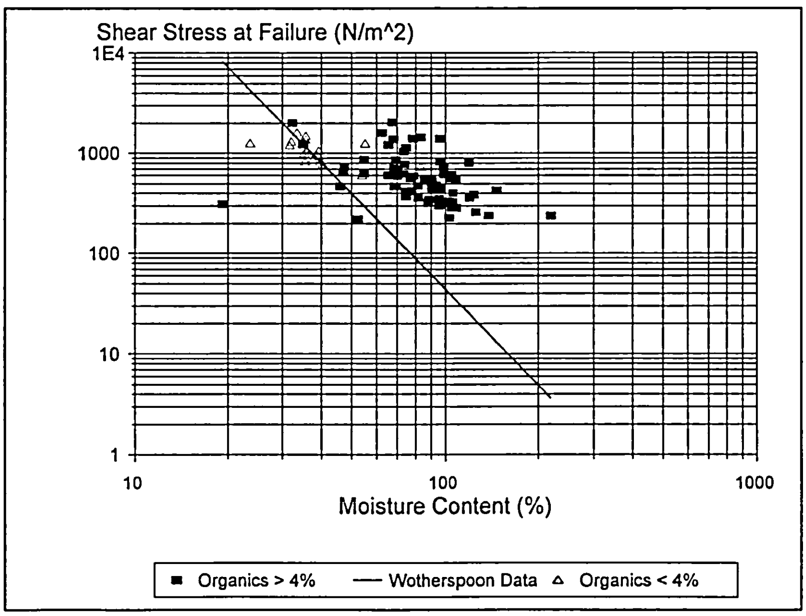

Figure G.3 : The role of organic content

The role of organic content was further analysed by plotting the parameter along the shear stress at failure for each of the data sets, as illustrated in Figure G.4. From this figure it can be seen that at lower organic content levels the parameter appears to have little influence. However as the organic levels increase the samples exhibit a reduction in yield stress.

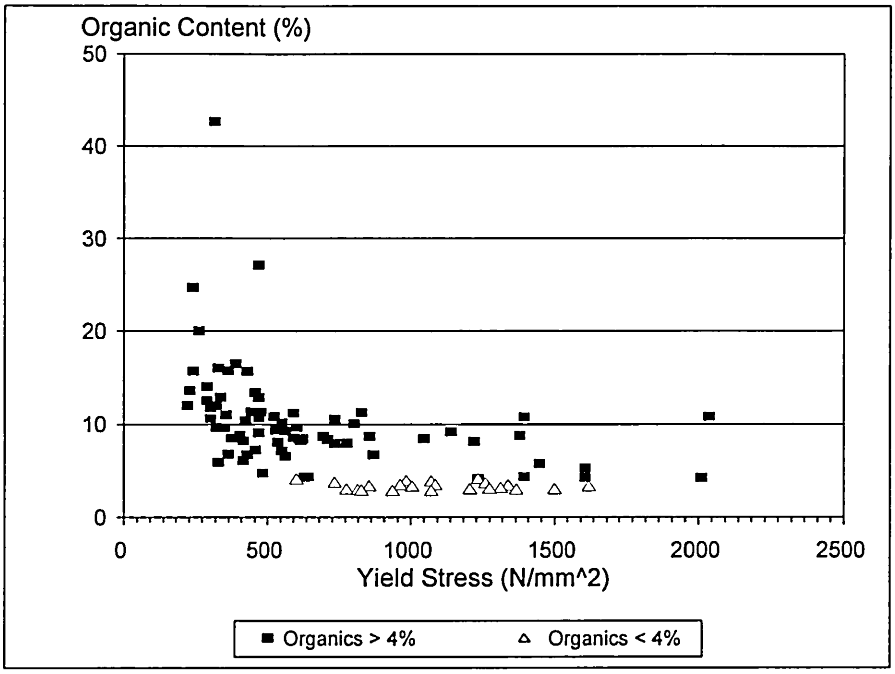

Figure G.4 : Yield stress variation with organic content.

These observations are only indicative as there is considerable scatter in the data plots, and no reliable relationships could be obtained. However the rheology testing undertaken as part of this study does indicate a possible limitation of the relationship obtained by Wotherspoon (1994). Additionally, the work has indicated that organic content is an import factor. However, it must be remembered that organic content and moisture content must be related, as indicated in Figure G.5. Additionally, organic content (and hence moisture content) were also observed to be related to sample density, as illustrated in Figure G.6.

The influence of organic content, and that of moisture content, may be due to the effect of reducing the interlocking between sediment particles. Although, an aged sample with high organic content may gain in strength due to increased cohesive *like* properties. However the rheological results reported here is only indicative and, clearly, more work is required in this area.

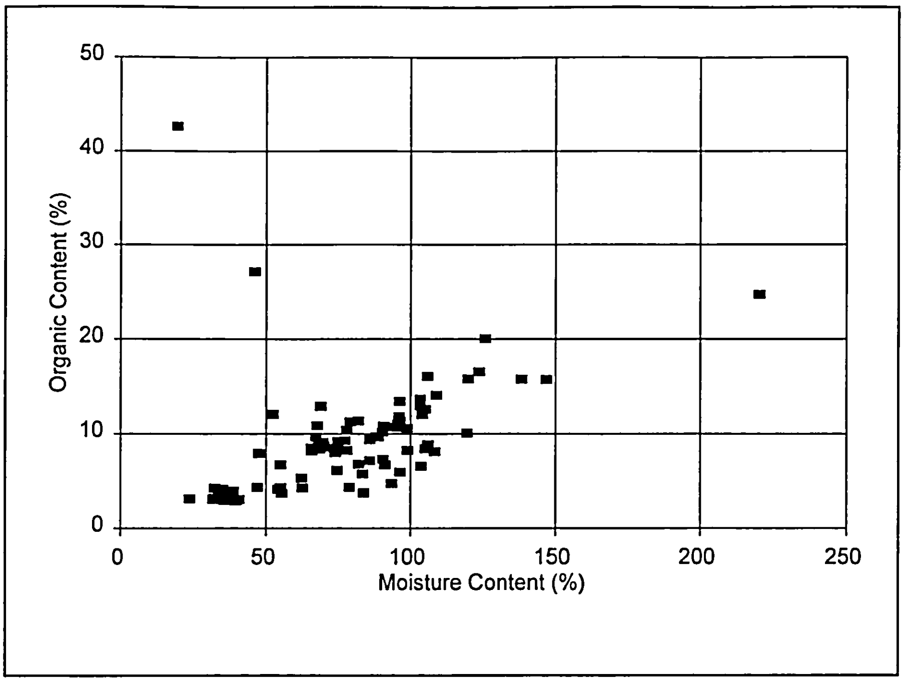

Figure G.5 : Moisture content variation with organic content.

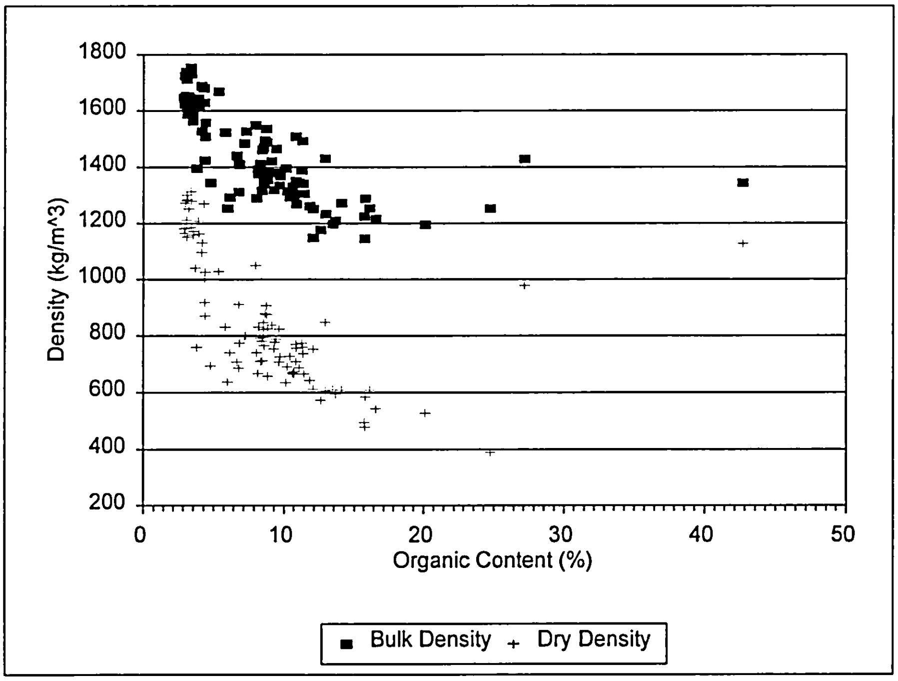

Figure G.6 : Density variation with organic content.

APPENDIX H : PLATES

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PLATE 1 : CONSTABLE STREET SILT TRAP

1. The plate shows the silt trap immediately prior to the installation of the test rig and the associated instrumentation used as part of Study Site 3.
2. On the wall, to the left of the plate, one of the channel sections which supported the test set-up can be seen.

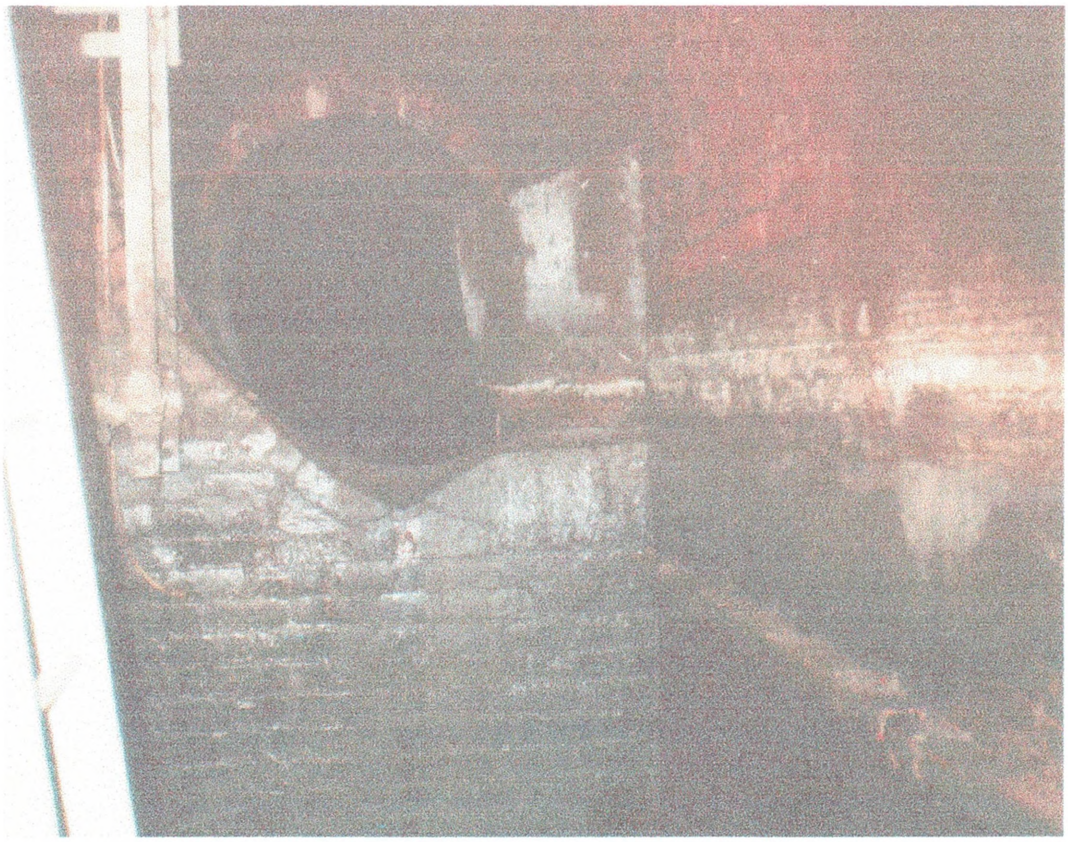


PLATE 2 : THE TEST RIG INSTALLED IN THE SEWER AT STUDY SITE 3

1. In the foreground of the plate the set-up used to sample suspended solids at two depths can be seen.
2. Due to the test rig surcharging during rainfall events the test rig rapidly became unsanitary.

PLATE 3 : THE TEST RIG AT STUDY SITE 3 SURCHARGING

1. As the 560mm internal diameter pipe usually had a flow depth approaching the pipe diameter, little capacity was reserved for storm flows. It was possible, however, to lower the DWF depths by means of a weir downstream, but this lead to excessive velocities (>1m/s).
2. Once flooded, the Study Site could be drained down by means of a pump supplied and operated by Tayside Regional Council Water Services Department. On one occasion, however, the working area had to be "bailed out" by hand due to a pump failure.

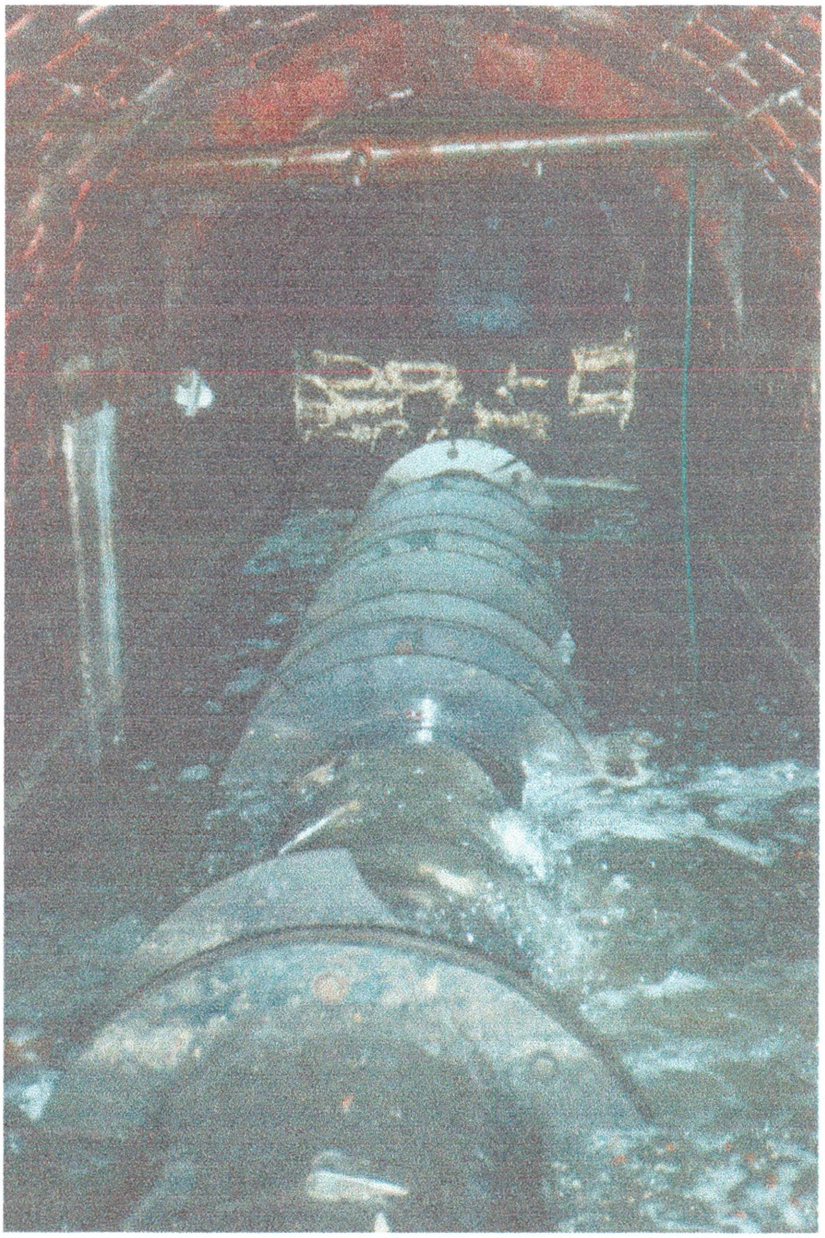


PLATE 4 : THE TEST RIG INSTALLED IN THE SEWER AT STUDY SITE 3

1. One of the temporary walls installed to provide a "dry" working area at Study Site 3 can be seen towards the end of the pipe in the plate.
2. The assembly used to obtain suspended solids samples at four depths can be seen towards the bottom of the plate.

PLATE 5 : TWO 1m LONG CLEAR ACRYLIC PIPES IN A STORE IN UAD IMMEDIATELY BEFORE INSTALLATION AT STUDY SITE 3

PLATE 6 : THE TEST RIG USED AT STUDY SITE 3 INSTALLED AT THE INTERCEPTOR SEWER STUDY SITE

1. The temporary wall installed to provide a "dry" working area at Study Site 3 can be seen towards the end of the pipe in the plate.

PLATE 7 : THE INVERT TRAPS USED TO OBTAIN SAMPLES OF NBS AT STUDY SITE 3 IN THE WWTC PUBLIC HEALTH LABORATORY IMMEDIATELY PRIOR TO INSTALLATION

PLATE 8 : THE INVERT TRAPS USED TO OBTAIN SAMPLES OF NBS AT STUDY SITE 3 INSTALLED IN THE TEST RIG

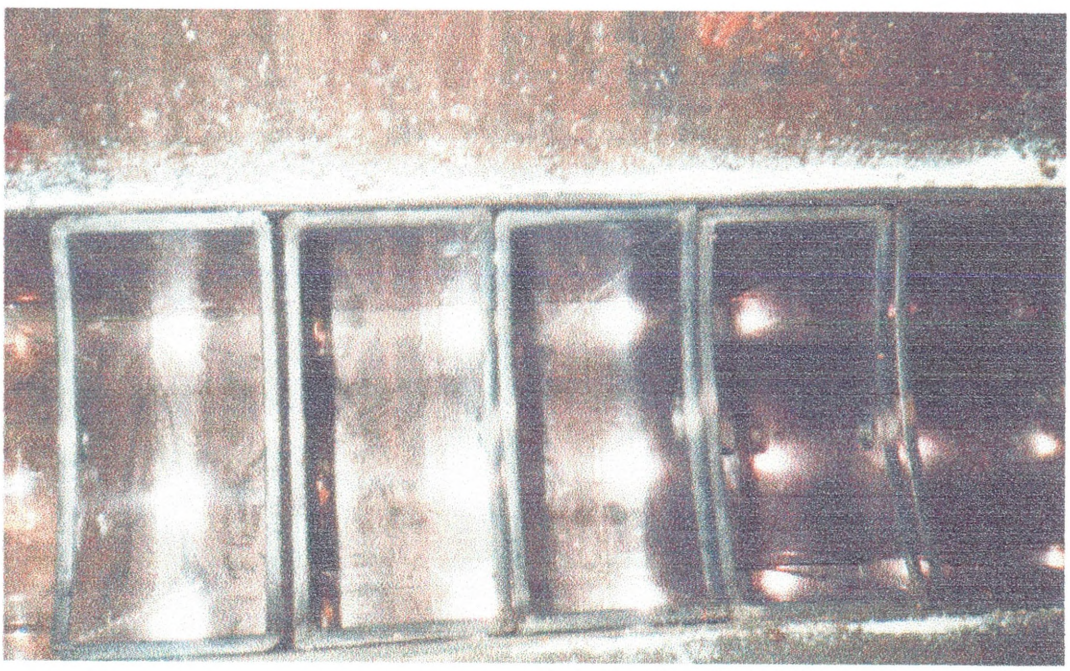


PLATE 9 : THE INVERT TRAPS USED TO OBTAIN SAMPLES OF NBS AT STUDY SITE 3 INSTALLED IN THE TEST RIG

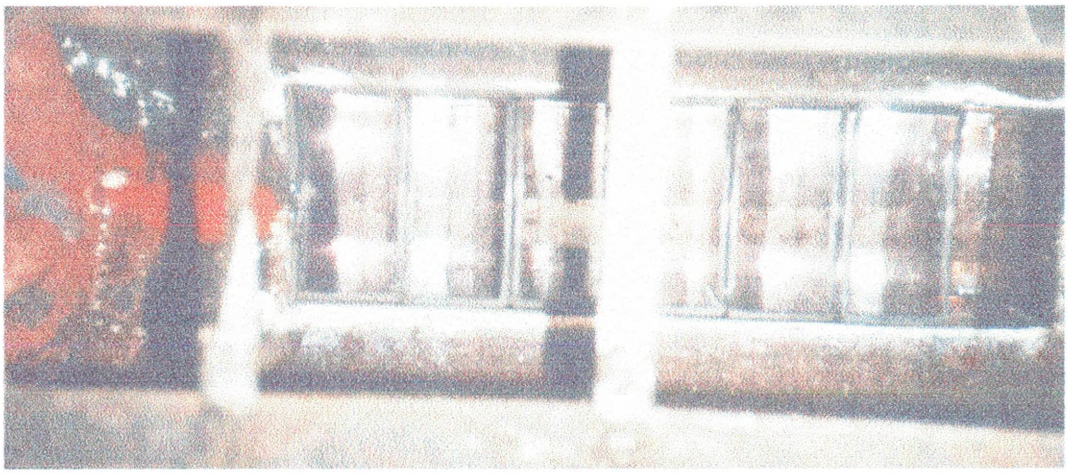


PLATE 10 : THE TEST ASSEMBLY USED TO OBTAIN SAMPLES OF SUSPENDED SOLIDS AT FOUR DEPTHS AT STUDY SITE 3

1. Samples were obtained through 4 rigid (copper) 10mm internal diameter pipes.
2. Copper pipes were used due to the ductility of the material.
3. During suspended solids collection, rags had to be continually removed from the sampling hoses.

PLATE 11 : FOUR EPIC 1011 PORTABLE WASTEWATER SAMPLERS STANDING ON THE ROAD SURFACE DURING SUSPENDED SOLIDS SAMPLING AT FOUR DEPTHS

PLATE 12 : NEAR BED SOLIDS SAMPLE OBTAINED FROM STUDY SITE 3

1. The plate illustrates how the upstream sediment traps were found to fill first, which was found to be the case at each of the data collection sites.

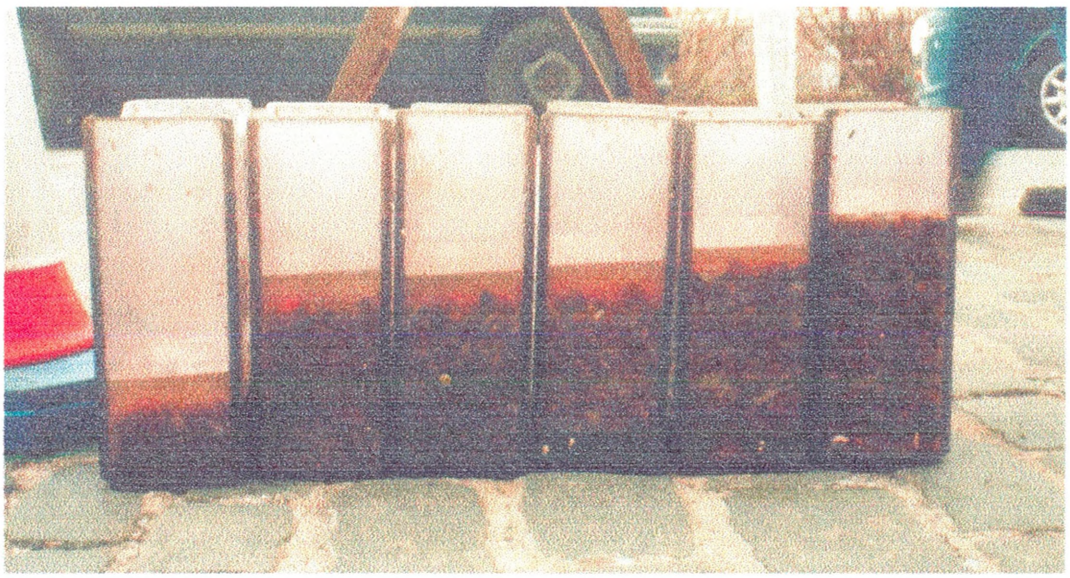


PLATE 13 : SAMPLES OF NEAR BED SOLIDS OBTAINED AT STUDY SITE 3 DURING THE NIGHT-TIME FLOW RECESSION

1. The plate shows how the NBS sampled during the night-time flow recession at Study Site 3 was predominately composed of broken down paper.

PLATE 14 : SAMPLES OF NEAR BED SOLIDS OBTAINED AT STUDY SITE 3 DURING THE NIGHT-TIME FLOW RECESSION

1. The plate shows how the NBS sampled during the night-time flow recession at Study Site 3 was predominately mad up of broken down paper.

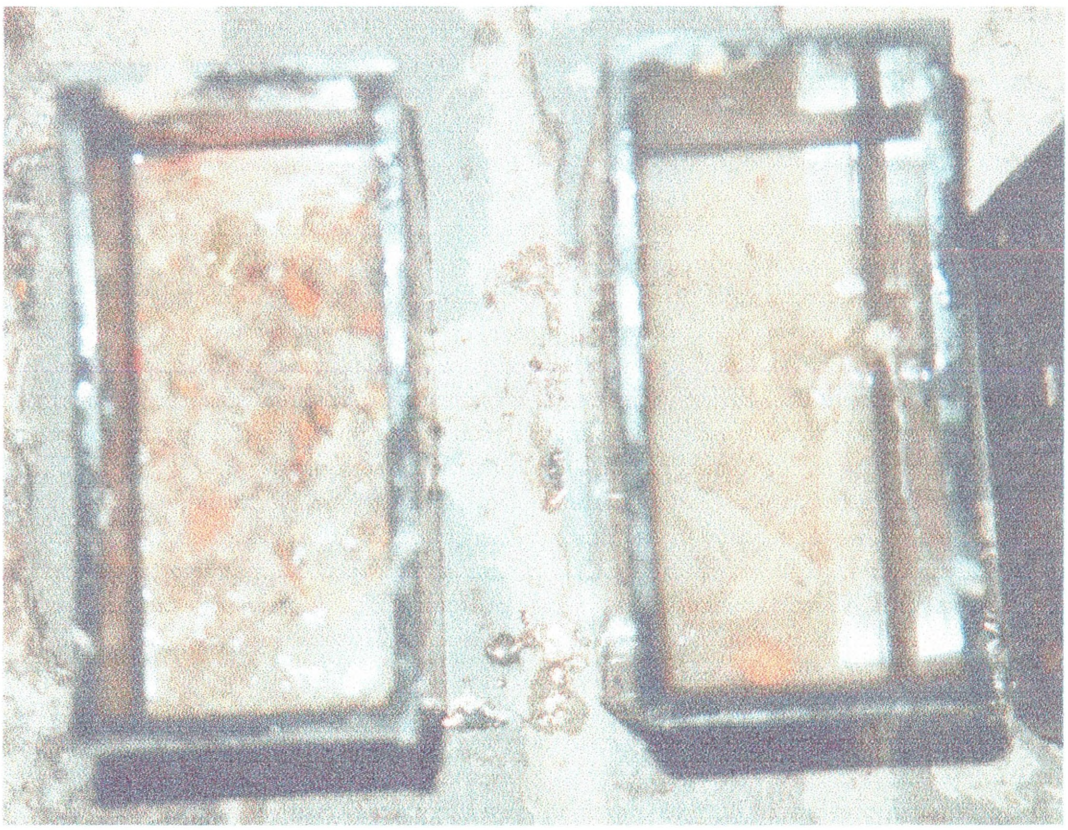


PLATE 15 : NEAR BED SOLIDS SAMPLED AT STUDY SITE 2

1. The plate shows both faecal and sanitary solids are represented in the near bed solids mode of transport.

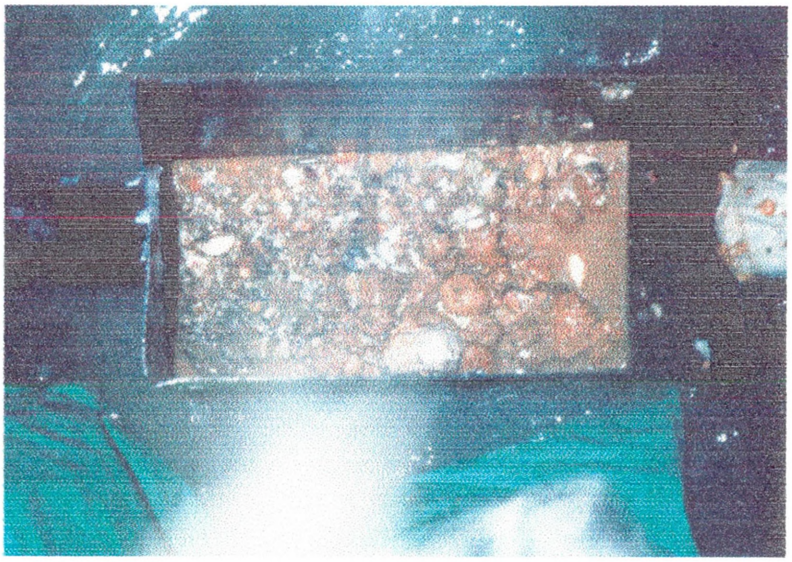


PLATE 16 : NEAR BED SOLIDS SAMPLED AT STUDY SITE 2

1. The plate highlights the diverse nature which comprises the material in transport at the bed.

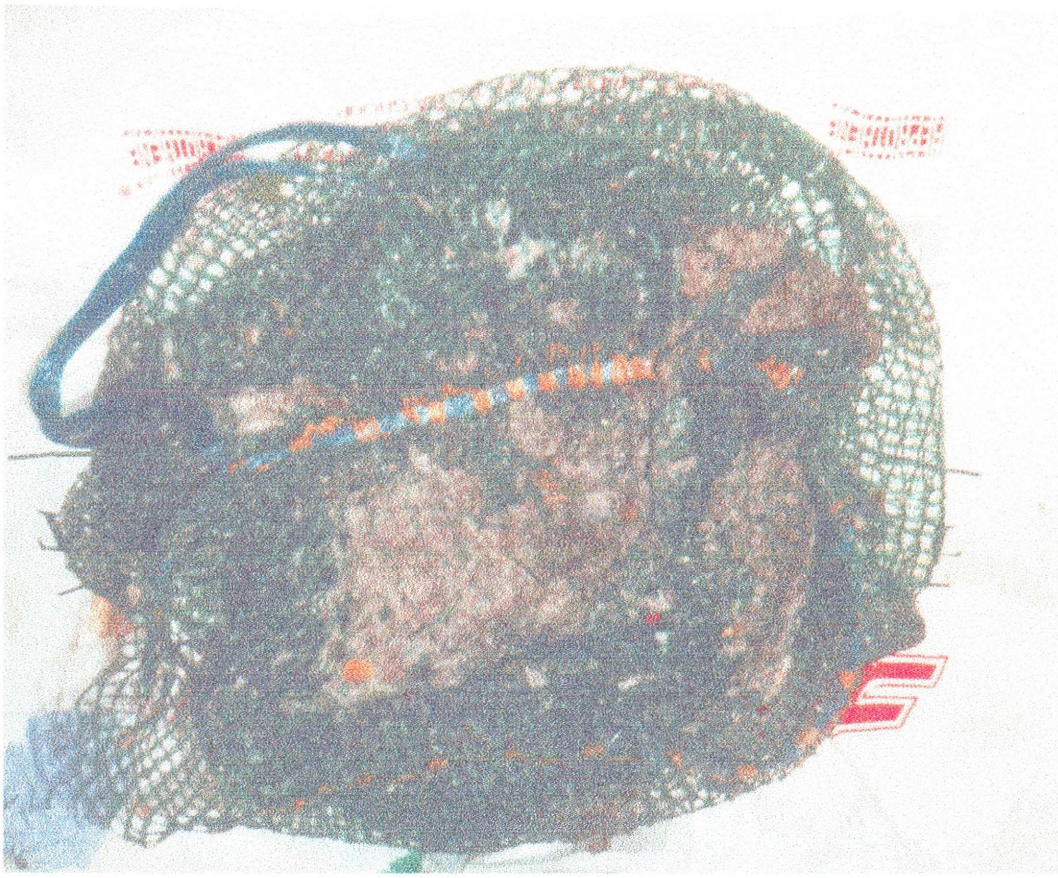
PLATE 17 : NEAR BED SOLIDS SAMPLED AT STUDY SITE 3

PLATE18 : NEAR BED SOLIDS SAMPLED AT STUDY SITE 3

1. The plate highlights the diverse nature which comprises the material in transport at the bed in the Dundee interceptor sewer.
2. The individual invert trap containers were removed by hand, through the flow column, at Study Site 3.

PLATE 19 : GROSS SAMPLE OBTAINED AT STUDY SITE 3

1. The plates show a Copa sack with 6mm mesh size, which were used to obtain samples of gross solids.
2. The plate indicates that the material in transport was predominately made up of broken down paper wastes.



APPENDIX I : PAPERS & OTHER OUTPUT - PUBLISHED AND IN PREPARATION

Arthur, S. & Ashley, R.M. (1997). The Influence of Near Bed Solids on First Foul Flush in Combined Sewers. The Sewer as a Physical, Chemical and Biological Reactor, Specialised Conference Aalborg. (Abstract Submitted)

Arthur, S. & Ashley, R.M. (1996). Sediment Transport at the Bed in a Combined Sewer. Proceedings of the 7th International Conference on Urban Storm Drainage, Hanover. (To be published)

Arthur, S., Ashley, R.M. & Nalluri, C. (1995) Near Bed Solids Transport in Sewers. Proc. Int. Conf. of Sewer Solids, University of Abertay Dundee, Dundee. (submitted for publication in Wat.Sci.Tech.)

Arthur, S. (1995), Sediment Transport at the Bed in Sewers. Presentation to the Scottish Hydraulics Study Group, University of Strathclyde, Glasgow.

Arthur, S., & Ashley, R.M. (1994). Near Bed Solids Transport in a Combined Sewer Network, WWTC, University of Abertay Dundee, Dundee. (Internal Project Report).

Ashley R M., Wotherspoon D J J., Arthur S., McGregor I. (in preparation) Sediment and pollutant erosion and transport in combined sewers. To be submitted to ASCE environmental Engineering Division.

Ashley, R.M., Saul, A.J., Nalluri, C., Arthur, S. and Skipworth, P. (1995), Behaviour of Sediments in Sewers, Final Grant Report - EPSRC Grant Ref : GR/H/43373, Wastewater Technology Centre, University of Abertay Dundee.

Ashley, R.M. & Verbanck (Ed), (1996), Sewer solids : State of the art, IWAQ, Scientific and Technical Review, Draft Report. (Co-author : Erosion and First Foul Flush Component)

Ashley, R.M., Arthur, S., Coghlan, B.P., & McGregor, I. (1994). Fluid sediment in combined sewers. Water Science Technology, 29, 113-123.

Ashley, R.M., Arthur, S., Coghlan, B.P., & McGregor, I. (1993). Fluid sediment and first flush in combined sewers. Proceedings of the 6th International Conference on Urban Storm Drainage.

McGregor, I., Ashley, S. & Arthur, S. (1997) Sewer Solids and their Associated Pollutants, The Sewer as a Physical, Chemical and Biological Reactor, Specialised Conference Aalborg. (Abstract Submitted).

APPENDIX J : MODEL APPLICATION

The aim of this appendix is to give an example of how the relationship proposed in section 5.4.2 "Independent Model Development" may be applied to data.

Example

For a storm which occurred in the Dundee interceptor sewer on 09.11.94 the contribution of the near bed solids mode of transport to the peak in TSS and COD will be estimated. From figures J.1 and J.2 it can be estimated that the peak TSS and COD are approximately 650mg/l and 800mg/l respectively, and that the peak occurs at approximately 06:15 (GMT).

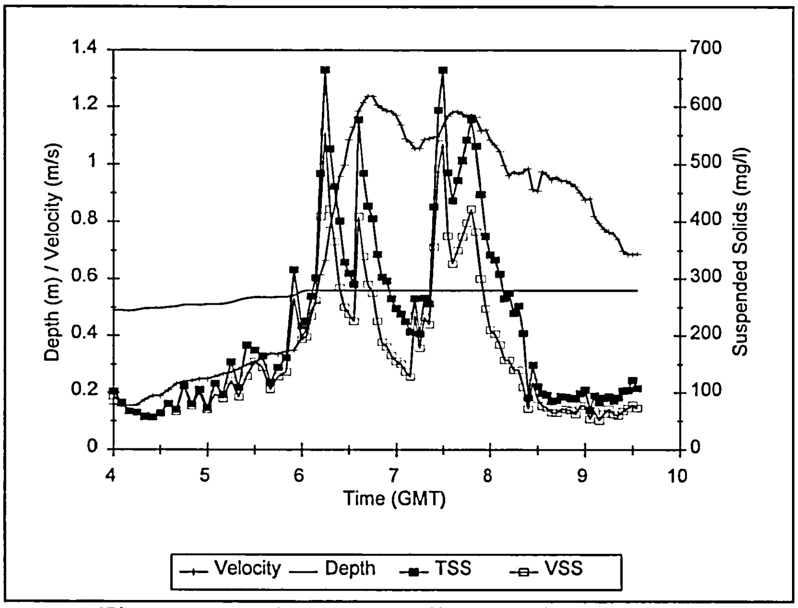


Figure J.1 : TSS storm pollutograph (09.11.94)

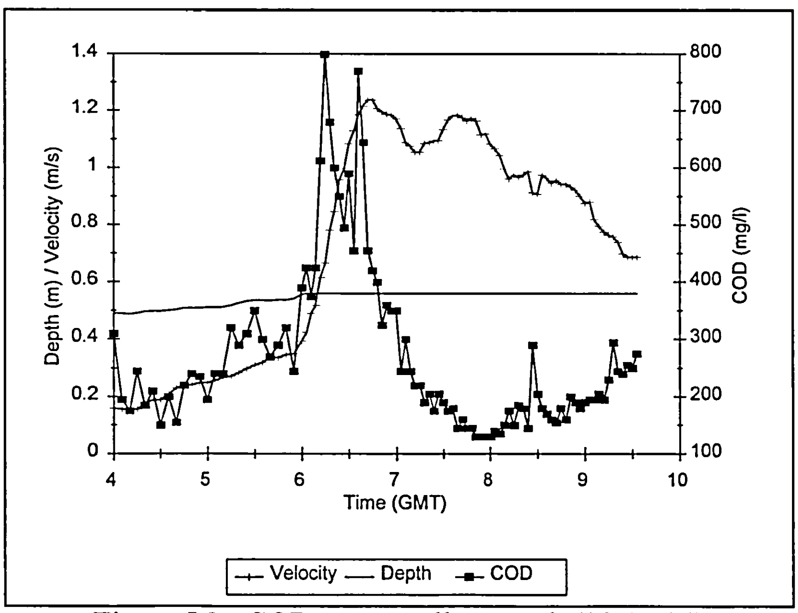


Figure J.2 : COD storm pollutograph (09.11.94)

From the data collected at Study Site 3 the following is known ;

Average DWF flow velocity at 06:15	0.15 m/s
Average DWF near bed velocity at 06:15	0.11 m/s
Average DWF Discharge	0.036 m^3/s
y_o/y_{max} (from figure J.3)	85.5 %
Average NBS Dry Density	80.7 kg/m^3
Average NBS Bulk Density	1000 kg/m^3
Average NBS Moisture Content	1350 %

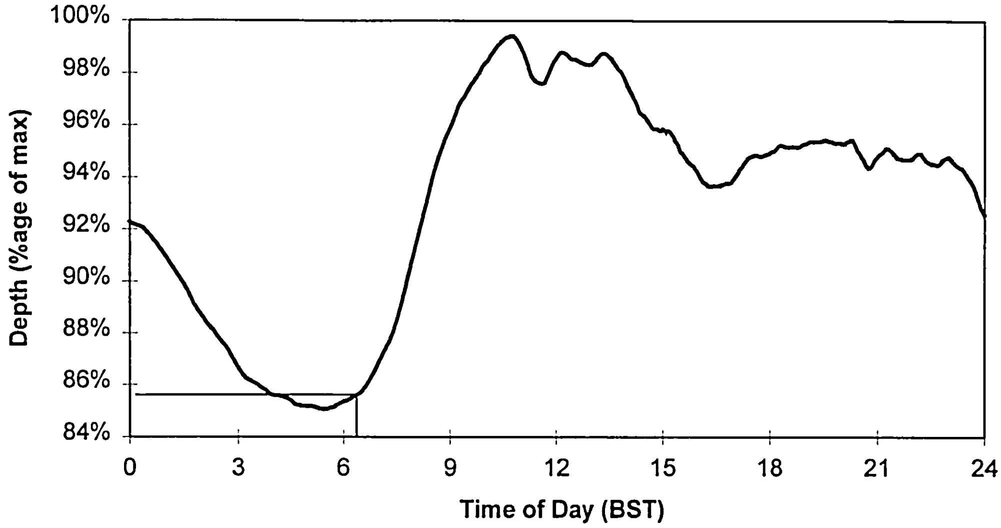


Figure J.3 : Average DWF depth variation - Study Site 3

From rainfall data, it was established that the last storm before that under consideration was that which occurred between 01:28 and 05:24 on 06.11.94. From the rainfall data for the 06.11.94, the following was determined:

Maximum Intensity, I_r	1.20 mm/h
Total rainfall Depth, D_r	1.20 mm
TSSS	76.8 hrs

Based on this data it is now possible to estimate the near bed solids transport rate using equation J.1.

$$C_v = -105.73 + 2.55\times 10^{-3}\left(\frac{I_r TSSS}{D_r}\right) + 0.2023\left(\frac{y_o}{y_{\max}}\right) + 47.808\left(\frac{\tau_o}{\tau_b}\right) + 120.45\left(\frac{\rho_d}{\rho_w}\right) \quad \text{....J.1}$$

The procedure is outlined in section 7.4.2.4 "Model Application", however more details regarding this example are given in the worksheet illustrated in Figure J.4.

As the results presented in Chapter 7 highlighted, the NBS mode of transport represents only a modest part of the total solids in transport. However, when the influence of COD level is considered, the impact is possibly considerable. The application of the methodology proposed as part of this project estimates that the near bed solids contributes at least 274mg/l of the total COD observed in the peak.

Upstream Sediment Characteristics

$I_r := 1.2 \quad D_r := 1.2 \quad TSSS := 76.8$

$$Upstream := \frac{TSSS \cdot I_r}{D_r}$$

$Upstream = 76.8$

Ambient Hydraulic Characteristics

$V_o := 0.15 \quad V_b := 0.11$

As the same relationship was used to determine the average shear and the shear at the bed, the term used to represent ambient hydraulic conditions may be simplified to:

$$Ambient := \frac{V_o^2}{V_b^2}$$

$Ambient = 1.86$

Inputs to the Syste m

$Inputs := 85.5$

Sediment Characteristics

$$Sediment := \frac{80.7}{1000}$$

$$C_v := -105.73 + \left(2.55 \cdot 10^{-3} \cdot Upstream\right) + (0.2023 \cdot Inputs) + (47.808 \cdot Ambient) + (120.45 \cdot Sediment)$$

$C_v = 10.382$ **ppm**

This represents only 10mg/l of the suspended solids in transport at 06:15.

Contribution of NBS to Peak COD

Wet Mass/Volume in transport

$Mass := C_v \cdot 36 \cdot 14.50 \cdot 10^{-6}$

$Mass = 0.005$ **kg/s - wet mass in transport at 06:15**

$$Volume := \frac{Mass}{1000} \cdot 1000$$

$Volume = 0.005$ **l/s - wet solids in transport at 06:15**

The COD concentrations of the NBS in transport were measured in the range 50600mg/l - 288000mg/l for Study Site 3 (see section 6.3.1.2 "Pollutant Characteristics"). Based on this range of NBS contribution (Min_{NBS} to Max_{NBS}) to the peak COD may be estimated.

$COD_{Min} := 50600$ **(mg/l)**

$COD_{Max} := 288000$ **(mg/l)**

$Min_{NBS} := Volume \cdot COD_{Min}$

$Min_{NBS} = 274.221$ **(mg/l)**

$Max_{NBS} := Volume \cdot COD_{Max}$

$Max_{NBS} = 1.561 \cdot 10^3$ **(mg/l)**

Figure J.4 : Worksheet illustrating the prediction of the COD impact of the NBS for the storm of 09.11.94

When assessing these results it must be remembered that sewage was sampled using a small bore sampler, and this may not be able to sample the material entrained from the NBS mode of transport due to the size of these solids. This means that the TSS and COD levels may be higher than illustrated in the pollutographs.

The results indicate, however, that the near bed solids mode of transport increases the suspended solids concentration by 10mg/l. However, perhaps more importantly, the COD concentration is increased by at least 274mg/l (42% of peak - 650mg/l).

Therefore, the methodology highlights the importance of the near bed solids mode of transport to first foul flush in sewers